How Much Is Too Much When the Earth Quakes?

The way last October's earthquake shook southern California generally vindicated seismologists' predictions, but some unusual shaking has raised engineering questions

The earth was in fearful agitation, with undulations so quick and rapid as to make it almost impossible to stand. The sensation was very much like that felt on the deck of a small vessel in a heavily chopped sea.—Comments of an observer of the great 1857 southern California earthquake.*

The study of the earth's shaking, bumping, and swaying during earthquakes has come a long way since the day when eyewitness accounts provided most of the information. Last October, earthquake engineers and seismologists combined advanced technology and thoughtful planning to make the most detailed measurements ever of the ground's shaking close to a sizable earthquake. As it turned out, the magnitude 6.6 Imperial Valley earthquake shook the El Centro area and northern Mexico about as hard as researchers had expected, which was a relief because observations within a few kilometers of a quake of that size had been few and widely scattered. Aside from reassuring seismologists a bit, the quake provided some interesting phenomena for them to ponder, such as its surprisingly strong vertical shaking and its sharper punch north of the border.

Structural engineers, who want to know how the shaking of the ground damages buildings, also had an unprecedented bonanza of data from instruments installed in the Imperial County Services Building, which suffered exceptionally severe damage during the earthquake (see box). These observations seem to have resolved most of the questions about the weaknesses in the building's design that might otherwise have remained a matter of opinion. But the interesting phenomena observed near the Imperial Fault have raised additional questions for engineers about the way they design structures such as nuclear power plants. Most of those questions are being raised by the Atomic Safety and Licensing Appeal Board of the Nuclear Regulatory Commission (NRC). It is asking whether, in light of the Imperial Valley experience, California's Diablo Canyon nuclear power plant, as now designed, might be considered to be too close to an earthquake-generating fault. Most engineers believe, however, that their methods have been conservative enough to accommodate the unusual shaking seen last October.

Before the Imperial Valley earthquake, seismologists and engineers could only make educated guesses about how hard the ground shakes near a rupturing fault, where much of the damage occurs. Only one record within 5 kilometers of a fault during a quake as large as Imperial Valley had been available. That close, the violent shaking knocks standard seismographs off scale and too few of the specialized accelerographs for measuring strong motion had been near even moderate quakes.

As the growing network of accelerographs recorded more and more events during the 1950's and 1960's, the maximum shaking observed rose sharply from about 0.3 to more than 1.2 times the acceleration of gravity (g). (The maximum acceleration, along with the peak velocity and peak displacement of the ground, are common measures of ground shaking.) However, the reliability of these isolated high accelerations remained a matter of debate. When someone had to estimate in 1972 how much shaking the proposed trans-Alaska pipeline might have to endure, Robert Page and his colleagues at the U.S. Geological Survey (USGS) in Menlo Park, California, concluded that a magnitude 6.5 earthquake would produce a peak acceleration of about 0.90g.

Engineers have made their own estimates of peak accelerations for use in designing structures such as the pipeline, but their estimates have not always agreed with those of seismologists. Since the 1940's, engineers had been inspecting earthquake damage and relating it to the few observed peak accelerations. From these measurements, many engineers had expected the highest peak accelerations to be below 0.5g. By the time of the pipeline planning, peak acceleration had become an often accepted guide to how much damage a structure might incur, but many engineers were having second thoughts even then. Too many buildings had weathered accelerations of 0.5g and more for there to be a simple relationship between peak acceleration and damage, they said. The practicality of the current approach to predicting damage, the use of "effective" rather than peak acceleration, will be examined this fall by the NRC's Appeal Board using the Imperial Valley data.

The Appeal Board is asking whether the shaking measured during the Imperial Valley earthquake should change estimates of the shaking that the Diablo Canyon plant might feel. One area of interest is the vertical versus horizontal shaking of the ground. When the Imperial Fault, one of a complex of faults that carries the San Andreas into Mexico, ruptured on 15 October 1979, the ground shook back and forth with a peak acceleration of up to 0.8g, as had been expected. But the ground near the fault heaved up and down with equal or even greater accelerations, which was generally unexpected. At a station 5 kilometers from the fault, the vertical acceleration was 0.93g, although in the horizontal it was only 0.51g. Less than 2 kilometers from the fault, an accelerograph measured an astonishing 1.74g vertical acceleration. Conventional engineering practice and NRC regulatory guidelines have assumed that vertical accelerations are two-thirds of the horizontal accelerations, or, in some cases, they may be

Earthquake Information Bulletin **9**, 22 (January–February 1977).

0036-8075/80/0829-1004$00.75/0 Copyright © 1980 AAAS

equal. According to the Appeal Board, the designers of the Diablo Canyon plant assumed that the two-thirds figure would apply in all cases.

Explanations for the relatively high vertical accelerations abound, although none has yet become widely accepted. Most explanations involve interactions between the seismic waves radiated by the rupturing fault and the deep layer of sediments underlying the Imperial Valley. For example, Ralph Archuleta of the USGS in Menlo Park suggests that the sediments might act like a focusing lens, bending waves back toward the surface that would otherwise be absorbed deep in the earth. The same happens to some seismic waves when they pass through the upper mantle of the earth.

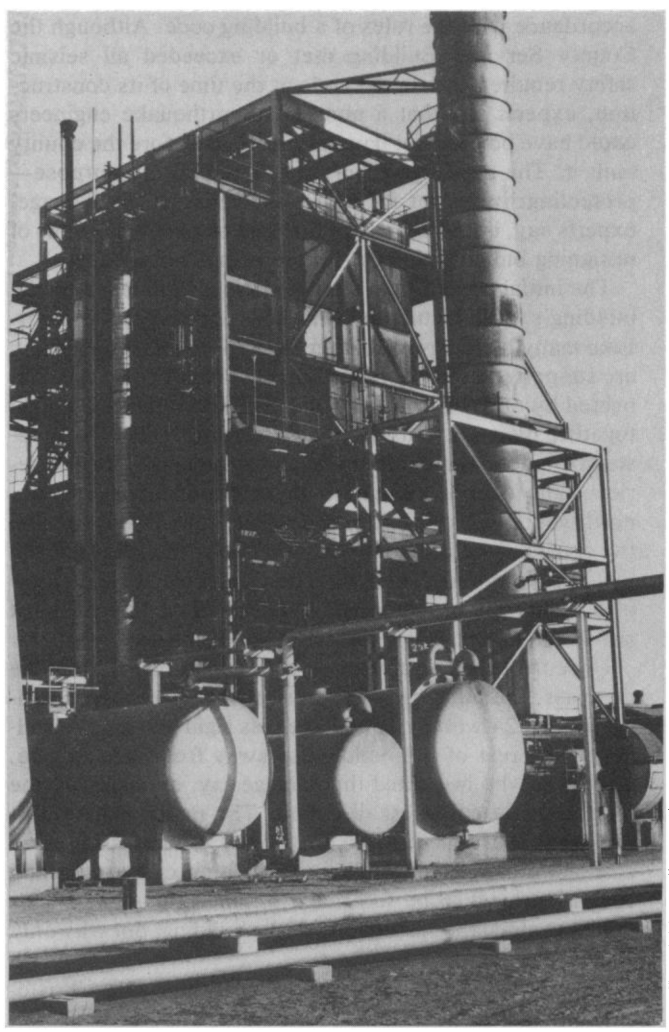
The extreme vertical acceleration of 1.74*g* may be a special case, according to David Boore and his colleagues at the USGS in Menlo Park. He recorded aftershocks with seismographs set up at the site northeast of the fault that was hit by the 1.74*g* acceleration and at the accelerograph site on the opposite side of the fault. Even when seismic waves arrived at the two sites from smaller, more distant sources than during the main shock, the site to the northeast of the fault registered higher vertical accelerations. Somehow, the arrangement of sediment and rock beneath that site may act as an amplifier of seismic waves, Boore says. Noel Bycroft, also of the USGS in Menlo Park, detected similar variability between two instruments only 200 meters apart, one of which recorded a peak vertical acceleration of 0.67*g* while the other recorded only 0.33*g*.

How the ground shook also depended on the location along the fault, which runs northwest across the border from Mexico and passes about 5 kilometers northeast of El Centro. The October earthquake began just over the border in Mexico but, according to Stephen Hartzell of the California Institute of Technology, the initial rupture extended only toward the northwest, not to the southeast, and it progressed in a series of halting steps rather than a smooth slipping along the fault. In Mexico, where the rupture was moving away, the shaking was more drawn out and of lower amplitude than in the United States where it was moving toward observers, Hartzell says.

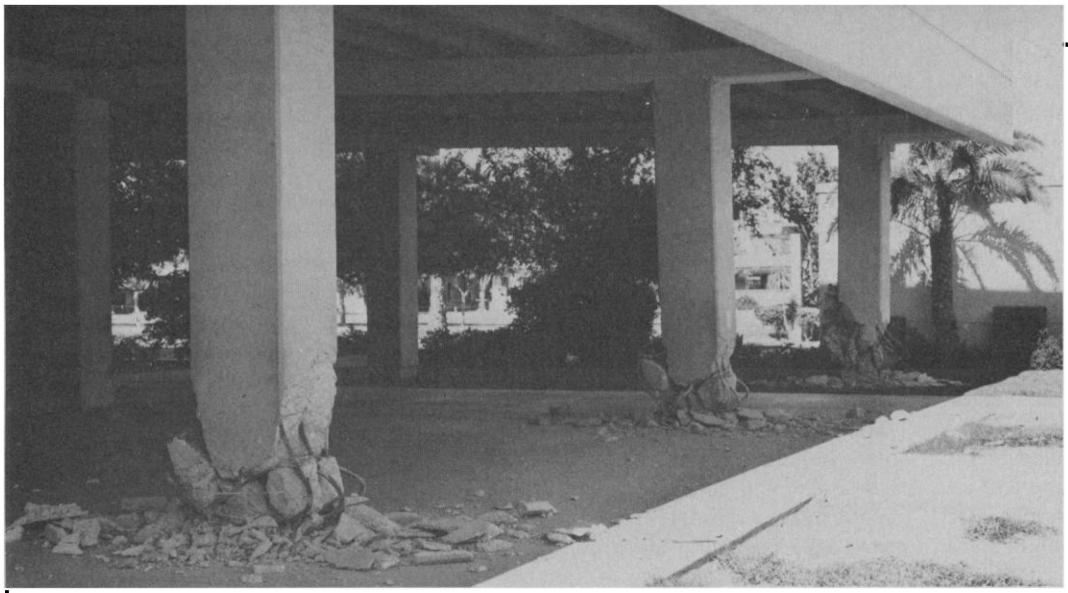
Archuleta explains that the seismic waves produced by the rupturing of the fault could travel only slightly faster than the movement of the rupture along the fault from Mexico. As a result, the waves tended to pile up in front of the progressively rupturing sections of fault, much the way air piles up in front of a jet approaching the speed of sound. This pile of waves produced a sharp pulse of ground motion near the fault, jerking the ground at one station 30 centimeters in one direction and then 45 centimeters in the other. This pulse may have contributed to the heavy damage of the County Services Building. Farther from the fault, the pulse dissipated into the more chaotic ground shaking observed in the past.

Most engineers believe that these and other phenomena of the Imperial Valley earthquake will make little or no difference in their estimates for Diablo Canyon. While preparing more detailed responses, they are pointing to their obvious successes. Aside from the County Services Building, which seems to have been a victim of now-obvious design problems, most buildings withstood the earthquake well. The centerpiece for many engineers was the El Centro Steam (Power) Plant, located only 5 kilometers from the fault. Although the four oil- or natural gas-fired units were designed and installed between 1948 and 1968, they suffered no significant structural damage, according to Joseph Martore of the NRC in Bethesda, Maryland. A few corroded, low-pressure water lines ruptured, one insulator broke on a transformer, and some steel supports bent, but the two units operating at the time of the quake were back in full operation within 5 hours.

The El Centro Steam Plant's performance interests NRC engineers particularly, Martore says, because it was designed according to standards and procedures nearly identical to those used in older nuclear power plants. The NRC is now reviewing the designs of such older plants, including their seismic safety. In the case of the El Centro plant, its designers simply assumed that during an earthquake each item would be accelerated at 0.2*g* in both the horizontal and vertical directions. This is called a static load design. Actual peak accelerations within 1 kilometer of the plant reached 0.67*g* in the vertical direction and 0.43*g* in the horizontal, according to Bycroft. Engineers attribute the plant's seismic resistance in part to the conservative ap-



The boiler and stack of one of the four units at the El Centro Steam (Power) Plant, which is 5 kilometers from the Imperial Fault. The magnitude 6.6 Imperial Valley earthquake caused only minor damage at the plant. This unit was again supplying power within 5 hours of the quake. [Photo by Otto Steinhardt]



Columns at the eastern end of the Imperial County Services Building after the Imperial Valley earthquake of 15 October 1979. The rocking and swaying of the five upper floors shortened the eastern columns, but no others, by about 20 centimeters. The wall in the left of the picture and three similar walls helped resist the shaking, but they were too far from this end of the building to save these columns. The building will be demolished, according to county officials. [*Photo by John Robb*]

Designing by the Rules Is Not Always Enough

Within seconds of the beginning of last October's earthquake, the eastern end of the six-story Imperial County Services Building sagged more than 20 centimeters as a row of columns beneath it crumbled. No one was injured, but the 10-year-old, $3 million building is a total loss.

Unlike critical facilities such as nuclear power plants (see story), which are designed according to a sophisticated, custom analysis, most buildings are constructed in accordance with the rules of a building code. Although the County Services Building met or exceeded all seismic safety requirements in the code at the time of its construction, experts say that a number of earthquake engineers could have pointed out flaws in its design before the county built it. The building design served its primary purpose—protecting lives—but its failure to minimize the damage, experts say, is an example of the unavoidable limitations of designing buildings in accordance with general codes.

The initial postmortem blamed the heavy damage on the building's architecturally attractive, open ground floor. Like many buildings in southern California, its upper floors are supported by reinforced concrete columns that are connected by only a few short walls. The upper floors are held together by solid walls at either end, which effectively resist the side-to-side motions of an earthquake. These exterior walls do not extend to the ground; however, four north-south walls do bridge the middle rows of columns on the ground floor at various points. Along the length of the building (in the east-west direction), a more flexible frame of columns and beams resists shaking in that direction, but not to the extent that thick, solid walls could.

Once the ground started shaking in every direction of the compass, the building behaved something like a rectangular box on 24 wobbly stilts. The less rigid ground floor allowed the rest of the building to sway from side to side, engineers who inspected the damage say, especially in the more flexible east-west direction. The upper stories also rocked back and forth, alternately compressing and stretching the columns. The combination of swaying and rocking proved to be too much for the four ground-floor columns along the eastern end of the building, but why only the eastern columns?

That "would have remained speculation," says Christopher Rojahn of the USGS in Menlo Park, "it was one person's opinion versus another's." The question perhaps might never have been resolved, he says, without the recordings made by the 13 accelerometers installed in the County Services Building by the California Division of Mines and Geology. They showed that, 7 seconds after the shaking started, the swaying in the longitudinal, east-west direction produced yielding and weakening of the structure, which further increased the swaying. This initial yielding coincided with the arrival of a pulse of seismic energy that may have helped weaken the building, Rojahn says. Four seconds later, the accelerograph system recorded high-pitched vibrations as the four eastern columns gave way.

The earthquake's shaking singled out the eastern columns for heavy damage because of the unsymmetrical placement of the four short north-south walls on the ground floor. The major source of stress on all of the columns, Rojahn says, was swaying in the more flexible east-west direction. It was the smaller stress of the rocking and the north-south swaying that caused the eastern columns to collapse. The short ground-floor walls could not help with the east-west swaying, but they did resist the north-south swaying and the rocking. With the placement of the nearest wall 9.5 meters from the eastern end of the building, apparently for reasons of function, the shaking put the greatest stress on those columns. The western columns, whose nearest transverse wall is only 2 meters away, suffered only minor damage.

Today's building code still allows open or partially open ground floors without the walls that would provide greater rigidity to resist earthquake shaking, but it does require more reinforcement of columns and it requires that an engineer judge how such an irregular building will react in an earthquake. The trouble, many engineers say, is that the behavior of the County Services Building or other irregularly shaped buildings in an earthquake is too complex to reduce to a set of rules in a code, and it probably always will be. In the end, they say, the fate of many buildings will still depend on the judgment of the engineer and the commitment of the building owner to conservative design.

—R.A.K.

proach traditionally taken in the design of such installations.

The design of modern nuclear power reactors, as well as other critical facilities such as major dams, bridges, and hospitals, is more sophisticated than that of the El Centro Steam Plant, but these designs have not yet been severely tested by an earthquake. Engineers using modern dynamic analysis recognize that each structure or piece of machinery, once set in motion, will vibrate at its own natural frequency the way a crystal goblet gives off its own tone when struck. Because seismic waves come in a whole range of frequencies, only certain waves can shake a particular structure. For example, seismic waves with a relatively high frequency of 15 hertz have little effect on a ten-story building, but they might vibrate piping or machinery. In the same way, the buildings of Imperial County College, which suffered no significant damage, did not "see" the exceptional 1.74*g* peak acceleration recorded there because it was at too high a frequency.

By using dynamic analysis, an engineer can decide if certain parts of the spectrum of seismic waves from an earthquake, such as the peak acceleration, can be de-emphasized in the design of a particular structure. For example, most structural engineers suspect that the high peak vertical accelerations of the Imperial Valley earthquake would have little effect on plant design because they were so brief and of such high frequency.

The delicate part of dynamic analysis is choosing an appropriate replacement, called the effective acceleration, for the observed peak acceleration. Numerous factors that might affect how hard a structure shakes, such as the underlying soil, the type of foundation, and the duration of the quake, must be considered, but such decisions are not entirely objective. "Only a handful of people in the world can do it," says John Blume of URS/John A. Blume & Associates in San Francisco. "A part of it is still judgment, although there is a lot of theory." Thomas Wosser of H. J. Degenkolb & Associates in San Francisco adds that "this earthquake design business is more an art than a science. Effective acceleration is a difficult thing to rationalize—it's a judgment call at best."

The NRC's Advisory Committee on Reactor Safeguards has made similar observations. When designers made modifications in the Diablo Canyon plant to accommodate the additional shaking expected from any earthquake on a newly discovered fault several kilometers away, the committee noted that "for want of better data, certain calculations were necessarily accepted largely on [expert] judgment and experience rather than on extensive observations or analyses, judgments not previously applied in approving power plant design."

Engineering judgment has provided the only guide so far as to why the Imperial Valley earthquake did not do more damage than it did. Many masonry buildings, which are usually the most susceptible, suffered little damage. Possible explanations remain qualitative and vague. Perhaps the shaking did not last long enough or was not violent enough; or, perhaps most of the masonry buildings had been tested by the 1940 Imperial Valley earthquake. Christopher Rojahn of the USGS in Menlo Park suspects, from inspecting the strong-motion record, that the shaking was not violent enough at the right frequency. It appeared to be strongest at the lower frequencies, which affect taller buildings such as the six-story County Services Building more than the typical one- to three-story masonry building. The quake would perhaps have done more damage, Rojahn says, if there were more buildings in the county taller than a few stories.

While noting that insufficient data have probably led to wasteful overdesign more often than dangerous construction, the National Research Council's Panel on Earthquake Problems Related to the Siting of Critical Facilities recently observed that "estimates [of ground motion] are subject to considerable uncertainties, reflecting the limited historical data base and the lack of detailed, quantitative knowledge of the influence of physical factors on ground motions. Data are particularly limited for near-field [close in] and large-magnitude earthquakes; unfortunately, such events pose the greatest hazard to structures." The Imperial Valley earthquake helped extend detailed observations to moderate earthquakes. The large quakes that may test structures such as the Diablo Canyon plant remain largely unobserved.—RICHARD A. KERR

Additional Reading

1. *Earthquake Research for the Safer Siting of Critical Facilities* (National Research Council, National Academy of Sciences, Washington, D.C., 1980), $8.50.
2. D. M. Boore *et al.*, *Estimation of Ground Motion Parameters* [U.S. Geological Survey Circular 795 (1978)].
3. *Architects and Earthquakes* (AIA Research Corporation, Superindent of Documents, Government Printing Office, Washington, D.C., Stock No. 038-000-00331-3), $2.20.

Lens Biophysics and Cataract Formation

Biophysical methods prove highly applicable to the lens

Most lens research centers on the problem of explaining cataract formation and of finding unifying theories to explain the many kinds of cataracts that can be induced to form in experimental animals. In general, the theories have had a biochemical basis and have applied to particular cataracts, such as those that develop in mice fed a high-galactose diet or those induced by ultraviolet light.

Only a handful of researchers have used biophysical techniques to study the lens, according to Oscar Candia, a biophysicist at Mount Sinai Medical School in New York. But the lens, it seems, is ideal for biophysical study because of its nearly spherical shape, which facilitates work with mathematical models, and because of its transparency. Among those taking a biophysical approach to lens research are James Rae, Richard Mathias, and Robert Eisenberg, who are physiologists at Rush University in Chicago. The three have used methods of biophysics and obtained results that suggest to them a new and functional theory of how the lens can maintain its volume and its transparency.

The Rush University group reported its results in June at a symposium entitled the Lens as a Biophysical Preparation, which was held during the combined meeting of the Biophysical Society

0036-8075/80/0829-1007$00.50/0 Copyright © 1980 AAAS