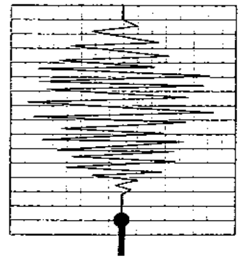
The Economist

A SURVEY OF EARTHQUAKE ENGINEERING

Fear of trembling



Fear of trembling

Two large earthquakes within a year have shown up our cities' fragility, writes Nicholas Valéry. Can engineers make them safer before the next seismic disaster?

IN THE milliseconds before the bed lurched violently across the room, the earth gave a primeval groan. Then came a creaking from the timbers of the three-storey building, followed by a thunderous heaving, grinding, crashing and finally a drunken swaying as the dust settled, broken glass tinkled and lights went out across the city of Los Angeles. Within 20 seconds, America's costliest earthquake ever had caused losses exceeding $20 billion. Then it was over—and your correspondent, along with 3.5m Angelenos, was struggling to find a flashlight and his shoes.

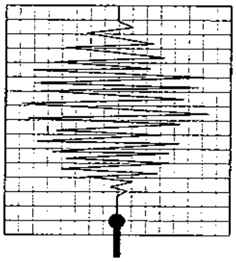
The Northridge earthquake which ripped through Los Angeles in the early hours of January 17th 1994 was not the "Big One" that has captivated Californians for decades. Measuring a modest 6.7 on the Richter scale, it packed less than a twentieth of the punch of the magnitude-7.5 (M7.5) quake that struck the nearby desert town of Landers in 1992. Yet the Northridge earthquake did a disproportionate amount of damage for its size. It picked up freeway bridges and smashed them to the ground, squashed brand-new multi-storey carparks, toppled structures considered earthquake-proof and shattered the engineering profession's faith in the integrity of modern steel-framed buildings. Thanks to a miracle of timing—it happened in the middle of the night before a public holiday—the Northridge quake was directly responsible for only 57 deaths. Had it come a few hours later, on a normal Monday morning, it could easily have killed thousands of people.

If Northridge sent shivers down the spines of seismologists and earthquake engineers everywhere, events in Kobe on January 17th 1995—eerily, one year to the day later—shocked them to the bone. Japanese engineers were convinced that their overhead road and railway bridges could withstand even the severest earthquake. Yet this time a middling-sized shock of M6.9 on the Richter scale laid waste to whole sections of Kobe, killing 5,470 people, injuring a further 33,000 and leaving 310,000 local residents homeless. The city's port, Japan's largest container facility, is expected to be out of action for a year or two. The cost of the Great Hanshin Earthquake—as the Kobe shock is now being called—has already topped $110 billion.

Unnervingly, neither the Kobe nor the Northridge earthquakes had been foreshadowed in local calculations. Both happened unexpectedly on small local faults rather than along the major boundaries where the most devastating earthquakes usually start, triggered by the headlong collision of newly-formed crustal material (or "plate") on the ocean floor with the ancient bedrock of continents.

One notoriously active plate boundary is the San Andreas fault, a 1,000km (620-mile) gash slicing through California. Another such zone is the necklace of troughs—Nankai, Suruga and Sagami—slung around the Pacific coastline of Japan. The Great Kanto Earthquake, the Big One that killed 142,000 people in Tokyo in 1923, sprang from Sagami Bay, where the ocean plate rubs up angrily against the ancient Eurasia plate.

Five years ago, the Japan Meteorological



Agency (JMA) compiled a map of the 18 apparently "earthquake-free" regions in the country that had experienced little or no seismic activity over the previous 30 years. The study took into account all tremors greater than M3 on the Richter scale and even allowed for active local faults and volcanic activity. Kobe was one of the 18 so-called quiet sites. A chastened JMA now views those sites as being not only not earthquake-free but especially vulnerable to future shocks.

The same lesson is being learned in all seismically active places around the world. Nowhere within 100km or so of a seismic fault is safe, however quiet it has been. The worries are re-emerging at a time when the classic "elastic-rebound theory" of earthquakes is beginning to look inadequate. That theory has served earthquake researchers ever since the San Andreas fault ruptured dramatically in 1906 and laid waste to San Francisco. It has held out the hope of perhaps one day being able to predict where and when the next big earthquake might strike. In essence, it compared the accumulation of stress along a seismic fault to a clock-spring. Once released by an earthquake, the stress would start building up again from zero, growing steadily and, it seemed, predictably over decades or centuries.

But large seismic events (and only large ones count) are proving to be nowhere near as predictable as was once thought. "Everywhere earthquakes seem to be a surprise," says Clarence Allen, a geologist at California Institute of Technology. They do not behave with clockwork regularity. Look at the earthquakes above M5 that have rocked California over the past 50 years (see chart 1 and table 2): statistically the pattern is random.

No one knows for sure what triggers a particular earthquake. In some places, the stress within a fault may build up until the pent-up energy is released with an almighty bang, as classical theory suggests. Elsewhere, a small rupture in the rock at some distant point may ripple through a network of interconnected faults, setting off a chain reaction that grows into a cataclysmic event. The rethinking of earthquake mechanics has barely begun.

Call me unpredictable

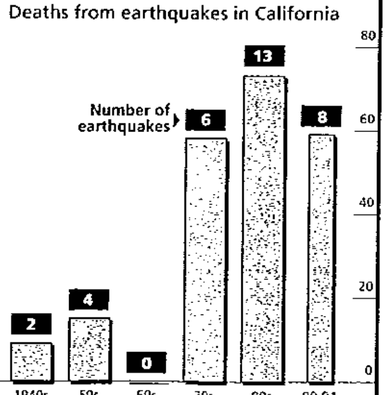
Meanwhile, people who live with the threat of earthquakes continue to put a great deal of faith in seismology's powers of prediction. Polls show that more than half of Japan's people believe that earthquakes can be predicted. Robert Geller, a seismologist at the University of Tokyo, regards this as dangerous. He points out that most residents in the Kobe area, expecting to receive advance warning of a major earthquake, neglected a number of common-sense precautions that would have saved countless lives. Mr Geller is not the only academic to believe that the Japanese government's huge research effort on earthquake prediction should be scrapped.

Yet not all seismological predictions are a waste of time. Rather than try to forecast where and when the next big earthquake will strike, it is better by far to use the resources to refine predictions on how, under given conditions, the ground is likely to move: how violent the shaking will be and how long it will last. Such insights help structural engineers design safer buildings and provide clues for shoring up older ones. Some seismologists are beginning to feel that the building codes in earthquake-prone parts of the world are based on unrealistically modest ground movement.

Both the Kobe and the Northridge earthquakes stunned experts by moving the ground much more violently than expected. At one place in the San Fernando Valley close to the Northridge epicentre, the ground accelerated sideways with a neck-snapping 1.8g (the acceleration due to gravity, g, is 9.8 metres per second per second). At the same time, the ground jerked upwards with 1.2g, more than enough to toss buildings and bridges into the air. The Kobe quake, though less dramatic, delivered peak accelerations of more than 0.8g laterally and nearly 0.5g vertically. These ground motions were

No rhyme nor reason **1**

Deaths from earthquakes in California



Source: California Seismic Safety Commission

Rogue's gallery **2**

Large earthquakes in California

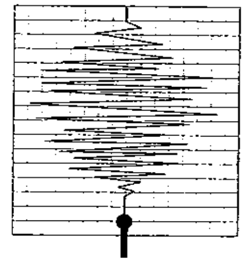
Location	Date	Magnitude	Deaths	Property damage, 1994, $m*
1990s				
Northridge	1994	6.7	57	20,000+
Big Bear	1992	6.6	0	96
Landers	1992	7.5	1	-
Cape Mendocino	1992	7.1	0	51
Cape Mendocino	1992	6.5	0	-
Joshua Tree	1992	6.1	0	-
Sierra Madre	1991	5.8	1	36
Upland	1990	5.5	0	11
1980s				
Loma Prieta	1989	6.9	63	7,100
Imperial County	1987	6.2	0	-
Imperial County	1987	6.6	0	4
Whittier	1987	5.9	8	467
Chalfont Valley	1986	6.0	0	-
Oceanside	1986	5.3	1	-
Palm Springs	1986	5.9	0	7
Morgan Hill	1984	6.2	0	14
Coalinga	1983	6.4	0	46
Eureka	1980	7.0	0	4
Owens Valley	1980	6.1	0	-
Owens Valley	1980	6.2	0	4
Livermore	1980	5.5	1	22
1970s				
Imperial Valley	1979	6.4	0	61
Gilroy/Hollister	1979	5.9	0	-
Santa Barbara	1978	5.7	0	16
Oroville	1975	5.9	0	-
Point Mugu	1973	5.9	0	3
San Fernando	1971	6.4	58	1,870
1960s	None			
1950s				
San Francisco	1957	5.3	0	5
Eureka	1954	6.6	1	11
Bakersfield	1952	5.8	2	56
Kern County	1952	7.7	12	280
1940s				
Santa Barbara	1941	5.9	0	-
El Centro	1940	7.1	9	64

Source: California Seismic Safety Commission *Adjusted by consumer-price inflation
Note: Table uses Richter magnitudes, not the more precise moment magnitudes

far stronger than the building codes allowed for. Los Angeles last time was remarkably fortunate to avoid huge loss of life and property. The Northridge earthquake struck a leafy suburb with few buildings older than 20 years or higher than a couple of storeys. Most of the earthquake's energy was directed harmlessly towards the Santa Susana mountains. Kobe, by contrast, took the full brunt of the rupture along the local Nojima fault.

Unfriendly neighbours

If there is one simple message to emerge from recent earthquakes around the world, it is that being distracted by the Big One is dangerous. In Japan, a preoccupation with the prospect of another Great Kanto Earthquake has left the rest of the country ill-prepared to cope with a disaster such as the recent Kobe quake. Likewise, in California, too much attention has been paid to the possibility of a megaquake of M8 on the San Andreas fault. Everywhere the risk of a modest earthquake on the doorstep needs to be taken more seriously. What, for instance, will happen to the 3.5m people on the east side of San Francisco Bay when the Hayward fault unzips from San Pablo to Fremont? The United States Geological Survey reckons there is a two-in-three chance of the Hayward fault rupturing with a M7 shock any time during the next 25 years. In Los Angeles, emergency measures ought to be focused on the cat's cradle of lesser faults beneath the metropolitan area rather than the San Andreas fault that runs 75km to the north-east.



This survey attempts to pull together what has been learned from the world's more devastating recent earthquakes. It focuses mainly on the engineering solutions that are being pioneered to protect people and their property when the ground suddenly ruptures and sends buildings flying. It looks at the kind of risk analysis that is now available for companies to minimise the disruption to business after an earthquake, and it examines the controversial issue of earthquake insurance to see whether that is the best way to buy protection.

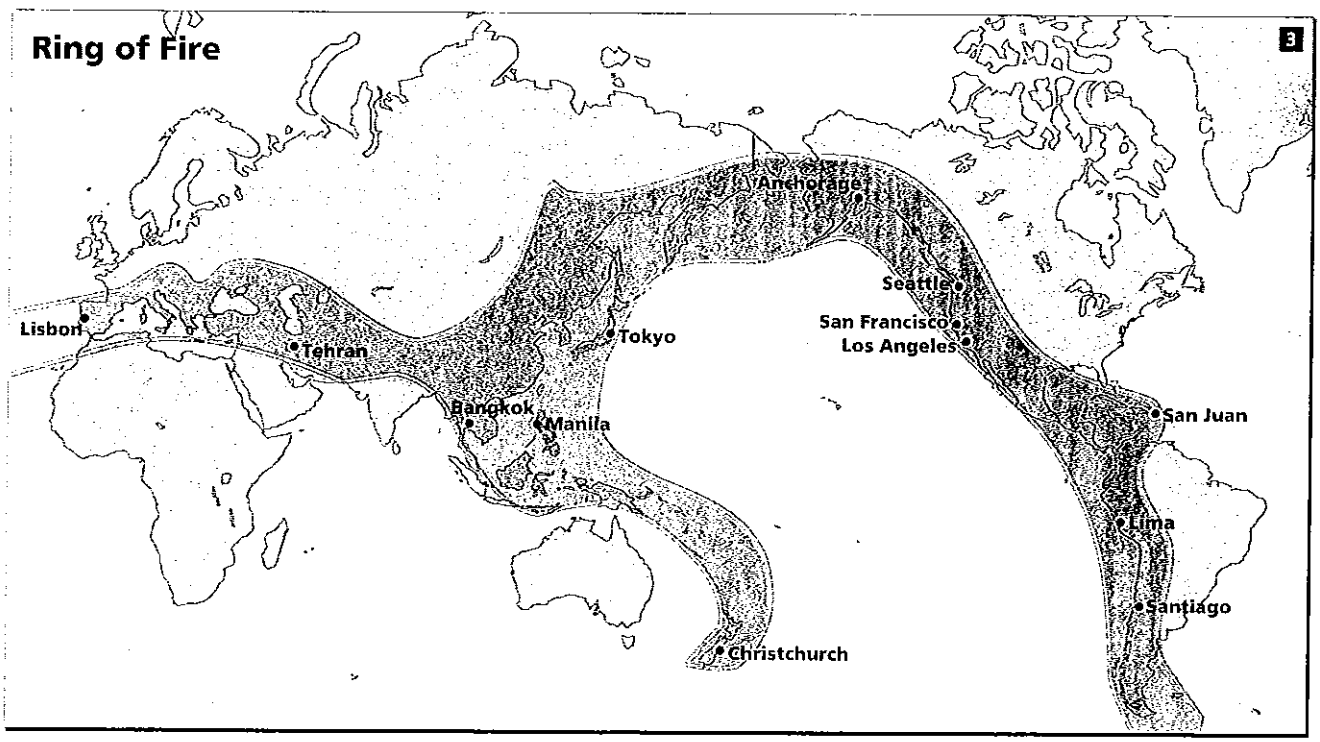
Inevitably, the survey draws heavily on findings in America and Japan, where long experience of seismology and earthquake engineering have already helped to reduce some of the risks. But first, a brief excursion into seismology. ■

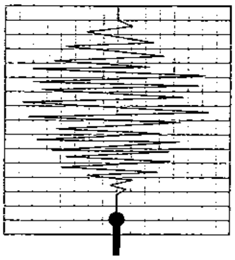
Shaky ground

Earthquakes are turning out to be more wayward than once thought

EARTHQUAKES are fuelled by the strains that build up as the earth's dozen or so tectonic plates jostle one another for space. Nowhere does this happen as ferociously as around the Pacific rim. The "subduction zones" where the thinner Pacific plate is forced beneath the thicker continental land masses account for three-quarters of the world's seismic energy.

This is the Ring of Fire—a 40,000km band of seismic activity that sweeps up the west coast of South and North America, across from Alaska to the Aleutians, Japan and China, and then down to the Philippines, Indonesia and Australasia (see chart 3). Over the centuries, earthquakes around this ring have claimed the lives of millions of people. The biggest disaster in recent years was in 1976 when a M7.8 earthquake hit Tangshan, 160km east of Beijing, killing 240,000 people. The previous major killer this century was the M7.9 shock that struck Tokyo in 1923, leaving 142,000 people dead.





The only other earthquake zone of any consequence—accounting for 15% of the earth's seismic energy—is a belt stretching west from the Bay of Bengal across the Himalayas to the Caspian Sea and the Mediterranean. This is where the Eurasian and African plates collide and form mountains, triggering earthquakes which have occasionally devastated cities of southern Europe, North Africa and the Middle East. One of the biggest to strike Europe was described by Voltaire in his novel "Candide". The earthquake that destroyed Lisbon in 1755 and rattled chandeliers as far away as Russia and America probably took about 60,000 lives.

By the mid-19th century, investigators had begun to notice that the damage caused by earthquakes tended to be concentrated in a fairly narrow geographical band, suggesting that they were caused by local phenomena. But it was not until the great San Francisco earthquake in 1906 that scientists began to pin down their cause. In a classic piece of seismic detective work, Harry Reid of Johns Hopkins University observed that fences and roads crossing the San Andreas fault in California no longer matched up. Such observations led Reid to propose the "elastic-rebound" theory of earthquakes. The concept has served generations of seismologists ever since.

The theory holds that the rocks on either side of a fault are elastic and can be bent back on themselves like a spring. As the crustal material on one side of the fault is pushed in one direction by the slow but inexorable forces of continental drift, friction from material on the other side of the fault restrains it, bending the material back until it suddenly ruptures or slips. One side of the fault then lurches forward against the other, releasing the pent-up energy that has been stored in the deformed rocks. If the blocks of crustal material slide past one another horizontally, the mechanism is known as a "strike-slip" fault. Where one block slides over another, the process is called a "thrust" or "dip-slip" fault (see chart 4).

When a thrust fault occurs underground, it is known as a "blind thrust". Such faults can be particularly mischievous, and not simply because they offer no surface clues to their whereabouts. When they rupture, they tend to shake the ground more vigorously and over a wider area than the more common strike-slip faults do. The Northridge earthquake last year was caused by slippage on a blind-thrust fault, which helps explain why it produced such violent ground motions.

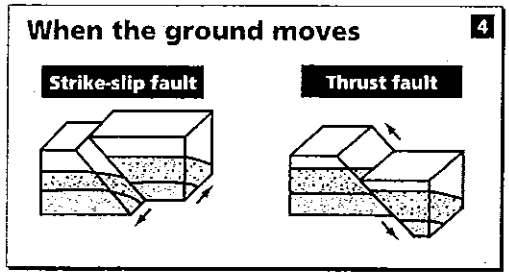
Seismic signature tune

Each earthquake broadcasts a signature tune of its own. A whole spectrum of seismic waves radiate from the fault at various speeds, depending on the kind of material they are travelling through. The telltale traces on seismographs give clues to an earthquake's origin, depth and size.

Of the shower of seismic waves generated by an earthquake, seismologists are mainly interested in three types: the kind that radiate across the earth's surface, and two kinds of body waves that travel through the earth's crust and mantle. Of the two body waves, one compresses the rock ahead of it as it rushes forward; the other shears the rock by elbowing it sideways as it travels in its partner's wake. Because the faster compressional waves arrive at a seismograph first, they are known as P-waves (for primary), while the shear waves are called S-waves (for secondary).

The most common way of measuring the magnitude of an earthquake is the scale invented in the 1930s by Charles Richter and Beno Gutenberg of California Institute of Technology (Caltech). The Richter scale is logarithmic. An earthquake of M7 represents a disturbance with ground motion ten times greater than one of M6. However, the amount of energy released by an M7 earthquake is more than 30 times that of an M6 quake. The scale is theoretically open-ended, but the largest Richter magnitude ever recorded was 8.9 for an earthquake off the coast of Japan in 1933.

However, at such magnitudes the Richter scale loses much of its meaning, and tends to underestimate the size of certain kinds of big quakes. Over the past 30 years a more sophisticated measure based on the "seismic moment" has been adopted by seismologists and earthquake engineers, reflecting the energy emitted by the entire fault instead of just a portion of it. This has forced some reassessment of old events. For instance, the earthquakes in San Francisco in 1906 and in Alaska in 1964 both registered around 8.3 on the Richter scale, but the seismic moment of the Alaskan shock was 100 times greater than that of its apparent equivalent in California. So the moment magnitude of the San Francisco quake has now been downgraded to M7.9 while that of the Alaskan one has been promoted to M9.2.



Large magnitude does not necessarily translate into violent ground movement. Much depends on the local geology. An area on top of unstable sand or clay is likely to be shaken up much more than somewhere at the same distance from the epicentre but sitting on granite.

This is where the concept of the seismic moment becomes particularly useful. Scientists have known since the mid-1960s that the seismic moment depends on the average slip of the fault, the area that is ruptured and the rigidity of the ground material involved. So if the details of a local fault are known, working out the average slip for an earthquake of a given moment magnitude becomes a relatively simple matter.

Take the Hayward fault which runs along the eastern shore of San Francisco Bay. Its main section is 50km long and 12km deep. If you know the dimensions of the fault and the rigidity of the local rocks, you can calculate what slippage to expect when the fault ruptures. If the Hayward fault ruptures from one end to the other, as it did in 1836 and 1868, it will produce an earthquake of moment M7.

causing one side of the fault to slip two metres against the other side. This is a crucial piece of information to help prepare for the worst.

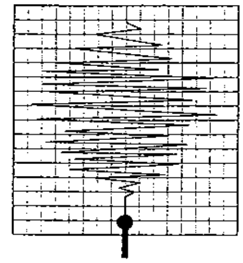
Most studies of what happens during an earthquake are based on records made by seismographs some distance from the epicentre. Instruments nearer the epicentre tend to get damaged by the effects of the quake. Only with the advent in recent years of robust little accelerometers to measure the g-forces on the ground has a clearer picture begun to emerge about the effects close by. The peak accelerations measured during tremblors over the past three years have given researchers pause for thought. One instrument near the Northridge epicentre picked up accelerations of as much as 1.82g—the kind of manoeuvre more usually associated with fighter aircraft.

Rapid accelerations sideways are bad enough. But when coupled with large displacements to and fro, the damage begins to get serious. The first hint that the ground close to an earthquake was doing something unexpected came in 1992 when a M7.3 tremblor hit the small town of Landers, north-east of Los Angeles. Poring over measurements made close to the epicentre, Wilfred Iwan of Caltech found evidence that the ground had moved 60cm away from the fault and then back again—all within five seconds. Mr Iwan has since detected similar "flings" among records collected near the epicentre of the M6.7 Northridge earthquake in 1994.

Such sudden displacements, forwards and then backwards, have worrying implications for tall buildings. If the footings of a large modern building are suddenly yanked a metre in one direction and then back again just as the upper floors of the building begin to follow the first yank, the structure may topple even if built to the most stringent of earthquake codes.

This problem has bothered Tom Heaton of the United States Geological Survey in Pasadena for several years. With colleagues at the neighbouring Caltech, Mr Heaton has made computer models of 20-storey steel-framed buildings and slammed them with hypothetical M7 earthquakes—typical of the type that lurk beneath Los Angeles. In the computer studies, the building swayed by as much as 6% in one direction and then snapped as it swung back. This suggests that had the Northridge earthquake struck downtown Los Angeles instead of a sleepy suburb 30km to the north-west, several skyscraper office blocks might have fallen down.

Seismologists at Caltech and elsewhere have calculated the amount of energy being stored within the rocks along the six main fault systems beneath the Los Angeles basin. Alarmingly, they have concluded that far too few largish earthquakes have taken place to relieve the stress that has accumulated over the past 200 years. In statistical terms, some 15 Northridge-sized earthquakes would be needed to pay off this deficit. Alternatively, the debt could be wiped out by one M7.5 megaquake—an event expected to recur once every 140 years or so. The last time Los Angeles had an earthquake that size was in the early 1780s.



Lessons from east and west

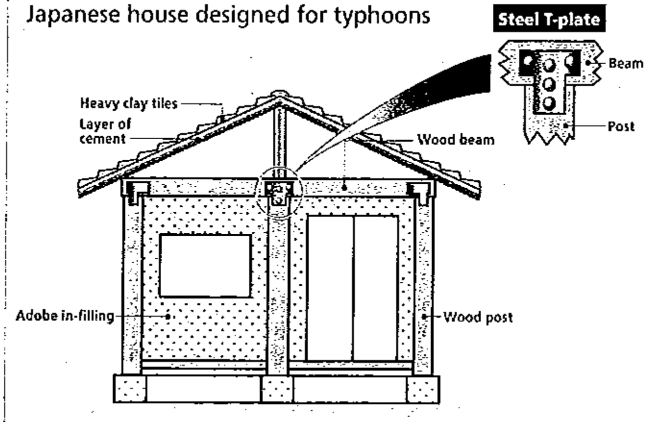
Be prepared—and be lucky

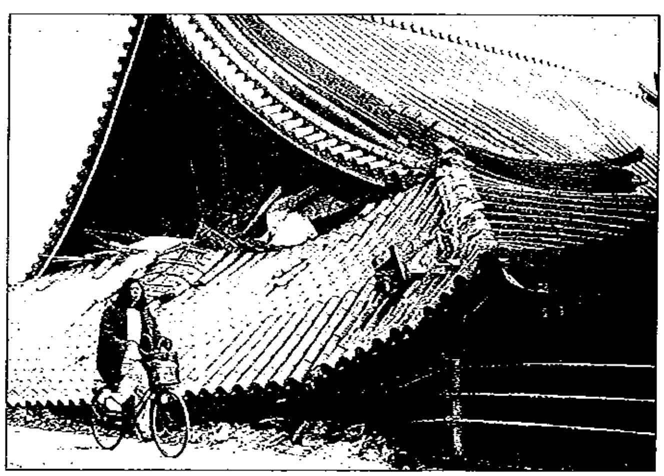
WHY the disparity in damage between the recent earthquakes that struck Los Angeles and Kobe? The Japanese earthquake was a little larger but the Californian one shook the ground more vigorously. Yet the Kobe quake caused damage estimated at $110 billion and claimed the lives of 5,470 people, while the rupture of the Northridge fault cost the community about $20 billion and killed 57 people. Three things made the difference—two of them whims of nature, one the outcome of structural design.

The Nojima strike-slip fault ruptured between Awaji Island and the mainland, then forked right along the Rokko fault through the most built-up part of Kobe. Los Angeles escaped serious damage because the blind-thrust fault that fractured under Northridge was directed harmlessly away from the downtown area towards the deserted Santa Susana mountains.

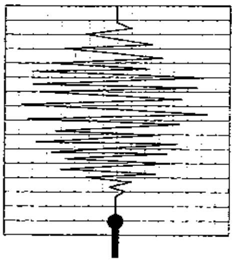
What made matters worse for Kobe was that the city is squeezed into a 3km-wide strip between the mountains and the sea. Most of it is built on soft

Blow me
Japanese house designed for typhoons





Don't shake me



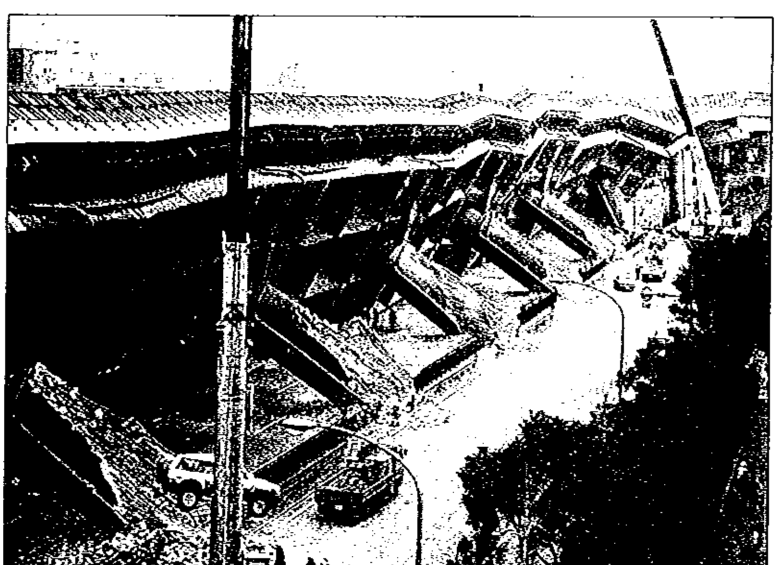
alluvial soil that has run off from the hillside over the millennia; closer to the shore it sits on lightly compacted land reclaimed from the sea. In an earthquake zone, such geology can spell disaster. The weak surface soils act as a lens focusing the seismic waves as they bounce off the underlying bedrock. Northridge, by contrast, is on much firmer ground that allows the seismic waves from the earthquake to pass straight through.

Despite Japan's seismic history, houses throughout the country have traditionally been built to withstand not earthquakes but typhoons, which are far more common and frequently more destructive. The Ministry of Construction's main priority is flood control rather than earthquake mitigation. The traditional Japanese house has a heavy clay-tile roof to withstand high winds, supported on vertical wooden posts resting loosely on boulders or shallow footings at the base and pegged at the top into horizontal beams (see chart 5).

Although the design of the traditional house is not specially adapted for earthquakes, it keeps the inhabitants reasonably safe in moderate shaking. The house sheds its roof tiles (locals are taught never to rush outside during an earthquake), reducing the load on the structure, while the loose-peg joints of the post-and-beam construction allow the building to sway. Usually, all that has to be done after an earthquake is to replace the missing roof tiles and replaster the cracked adobe walls.

But until January 17th, no one in living memory had experienced a moderately large earthquake right beneath a large urban area in Japan. The ground motions recorded in Kobe were twice as dramatic as those during the M8.2 Great Kanto Earthquake of 1923 in Tokyo. In the Kobe quake, houses had their footings kicked out from under them before the swaying even began. The heavy roofs immediately came down, crushing the inhabitants in their sleep. This is how over 90% of Kobe's 5,470 victims died.

Both the Northridge and the Kobe earthquakes happened in the early hours of the morning when most people were asleep. In California, where houses have stiff wooden frames braced with sheets of plywood and topped with light wooden roofs, the safest place for people during the earthquake was in bed. In Kobe, that was just about the most dangerous place to be.



A Japanese road to ruin

Unpleasant surprises

But Northridge brought its own shocks that have forced structural engineers to reassess their safety measures. No type of building came through the earthquake unscathed. Indeed, some performed so badly that their design may never be used again, either in California or elsewhere.

Among the more lethal were three-storey apartment buildings framed in wood and clad with sheets of gypsum board or stucco. More than 200 apartment blocks collapsed or had to be pulled down; a further 650 suffered serious damage. Such buildings either have carports beneath them or a garage occupying the whole of the ground floor, with few dividing walls to resist the sideways shearing forces unleashed by an earthquake. Helmut Krawinkler of Stanford University wonders whether Californians put too much faith in the good performance of wood in structures which depend critically on nails and other fasteners for their integrity, and use brittle panelling.

Another of Northridge's nasty surprises was the collapse of a number of modern multi-storey car parks. Almost all of them used long precast sections of concrete. Most failed when the vertical concrete columns were bent sideways by the shaking until they cracked, causing the horizontal concrete beams supporting the floors above to come tumbling down. Californian building codes for precast concrete car parks have been hurriedly revised.

Buildings that performed badly in the Northridge earthquake also included many of the reinforced concrete office blocks put up more than 20 years ago. The regulations governing such buildings were changed in 1973 to require more steel reinforcing bars (rebars) to be included in the concrete. Some of the older concrete buildings failed catastrophically during the Northridge earthquake; others were left leaning so badly they had to be pulled down. Though none of the post-1973 reinforced concrete buildings collapsed, a number suffered significant damage—largely because walls and roofs were not anchored together properly.

But the biggest engineering shock by far to come out of the Northridge earthquake was the failure of one of the most popular types of steel-framed buildings in use. The so-called "moment-resisting frames" are lighter and stronger than other designs. They are rigid because, apart from being bolted together, the top and bottom of the crossbeams at each joint are welded to the vertical columns. Moment-resisting frames have become popular because they are cheap and easy to build and, until the Northridge disaster, were considered outstandingly good at handling earthquakes.

In the weeks after the Northridge earthquake, a few moment-resisting buildings were found to have cracks in the joints where the steel beams are welded to the vertical columns. On more careful examination, more than 120 such buildings throughout the Los Angeles area revealed similar cracking. Though few showed any outward signs of failure, it was clear that some would not have survived another serious earthquake.

The city of Los Angeles has now clamped down on the use of this form of construction. The municipal authorities have also demanded a thorough inspection of some 300 moment-resisting buildings in the badly shaken parts of San Fernando Valley and West Los Angeles. If more than half the joints on any one floor show signs of cracking, the building will have to be repaired and strengthened. The inspection alone is expected to set owners back more than $300m. Searching questions are now being asked about the design itself. This is a huge blow for the construction industry worldwide: the design was used in over half the commercial buildings erected around the globe last year.

Japan is no exception

All told, the recent Kobe earthquake wrecked some 100,000 buildings. It revealed every conceivable form of structural damage, including fractures around the welded joints in steel-framed buildings. Older reinforced-concrete buildings collapsed in Kobe in much the same way as they did in Los Angeles. Concrete columns, unable to withstand the sideways shearing forces of the quake, burst open as the steel hoops meant to restrain the vertical reinforcing bars inside the concrete snapped. This is what happened to the mighty columns supporting the Hanshin Expressway, causing it to topple on its side. A year earlier, engineers with the California Department of Transportation (Caltrans) had looked enviously at Japan's expressways when half a dozen freeway bridges in Los Angeles collapsed during the Northridge earthquake. Japan has traditionally built much sturdier elevated roads, with columns 50% fatter and containing two or three times more reinforcing bars in the overhead spans. Caltrans, by contrast, has used a lighter, more flexible design for its overpasses.

But most of the overhead road sections that collapsed in the Northridge earthquake had been built before 1971 and were waiting to have reinforcing hoops retrofitted within their concrete columns. More modern bridge spans, as well as older ones that had already been retrofitted, came through the Northridge shaking unscathed. Earthquake engineers on both sides of the Pacific now wonder if the Japanese column design is too massive.

One of the most common forms of structural failure in Kobe, aside from traditional housing, was among typical ten-storey buildings that collapsed around mid-height. The Architectural Institute of Japan believes this was caused by a resonance effect as shockwaves travelling up through the building collided with shockwaves travelling back down after bouncing off the roof. Maybe. But Japanese building codes prior to 1981 required the use of steel inside the columns of a reinforced concrete building only up to a height of 16 metres—in such a building, roughly the fifth floor.

Kobe's experience shows that, in an earthquake, treacherous soils hold special dangers. Like many sections of Los Angeles, San Francisco, Oakland, Portland and Seattle, Japanese coastal cities are built on loosely compacted sediments and marshy tracts that have been reclaimed from the sea with landfill. Apart from focusing and amplifying the seismic waves bouncing off the bedrock below, such soft soils lose what little strength they have when subjected to violent shaking, and swiftly turn into quicksand. This "liquefaction" process undermines the foundations of buildings, harbour walls and bridge piers, hastening their collapse.

Earthquake engineers are learning by trial and error how to ease the liquefaction problem. They have developed techniques for compacting the loose soils with vibrating probes and buried columns of crushed stones. But such measures are costly and time-consuming. In the meantime, the only way of protecting structures that must sit on such shifting soils is to ensure that the foundations are anchored firmly to the bedrock below.

Managing risk

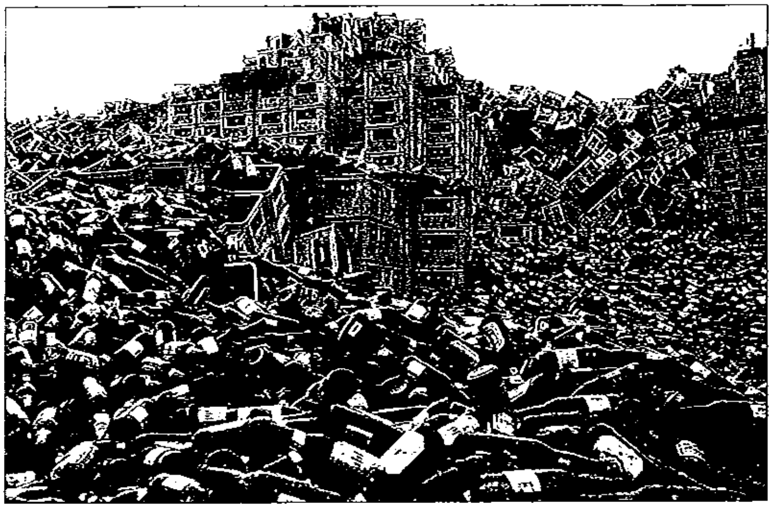
Prevention is cheaper than cure

EARTHQUAKES do not come cheap these days. Bigger, fancier commercial buildings, the increased use of elevated roads, houses sprawling everywhere, and communities that have grown dependent on being able to commute to work have bid up the price of urban disasters. Even a modest tremblor striking an urban area is likely to cause damage costing at least $30 billion-50 billion. Counting everything, that is roughly what the Northridge earthquake added up to. A re-run of the M7.9 earthquake that destroyed San Francisco in 1906 would cause damage of around $115 billion to the vastly bigger, more complex bayside city of today, reckons Haresh Shah of Stanford University.

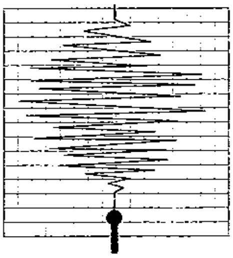
In high-cost Japan, the bills come bigger still. The Kobe quake, for instance, has already notched up $110 billion. Charles Scawthorn of EQE International, a safety-engineering consultancy based in San Francisco, puts the total damage in Kobe at $150 billion-200 billion, or about 4% of Japan's annual gross domestic product (GDP). A repeat of the earthquake that flattened Tokyo in 1923 could cost anything from $900 billion to $1.4 trillion today—a huge amount of money to find for even the wealthiest of countries.

Costs would be even higher but for one thing: casualty numbers have declined dramatically in the past 20 years, thanks to building codes that have made modern homes, workplaces and public facilities far safer. Earthquake engineers' main aim today is to save people, not buildings. But with the cost of earthquakes rocketing out of sight, interest is now focusing on the technological feasibility of preserving the building as well, with the proviso that people's safety must remain paramount. What is emerging from all this is a whole new philosophy for managing risk. The idea, in a nutshell, is to make insurance irrelevant.

The economic costs of an earthquake to a business do not stop with repairing and replacing damaged buildings; interrupted trading and increased unemployment must be added on top. Japanese



Trouble brewing in Kobe



carmakers, for instance, lost production of 40,000 units worth $350m during the month after the Kobe earthquake. Production elsewhere had to be suspended because of shortages of parts made in the Kobe area. Surprisingly, few Japanese car companies had contingency plans for switching to alternative suppliers in an emergency.

Daiei, Japan's largest chain of supermarkets and department stores, had no back-up plans ready to swing into action if its headquarters were wiped out by a disaster. The January 17th earthquake cost Kobe-based Daiei $500m in damages and lost business, pushing the company into the red for the first time ever. Sumitomo Rubber, founded in Kobe at the turn of the century, was wholly unprepared for an earthquake, and is now having to rebuild from scratch. It has chosen a site in Nagoya, some 150km away from Kobe.

Planning for the worst

With hindsight, it is easy to say that Kobe should have taken the possibility of an earthquake more seriously. In seismically vulnerable places elsewhere, companies are learning to be more circumspect. Disaster planning is catching on, particularly among organisations with headquarters in Tokyo. But it is California which has made the most progress with minimising the risk of business interruption. Engineering consultancies such as EQE International, Woodward-Clyde, Risk Engineering and Rutherford & Chekene make their living from helping corporate clients prepare for the worst while hoping for the best.

Anheuser-Busch, a beer company with one of its main breweries in the San Fernando Valley region of Los Angeles, decided some years ago that under no circumstances could it afford to lose the output from the plant. Over a period of time it spent $30m on disaster-planning, including contingency plans for alternative water supplies. When disaster did strike, the company saved more than $300m by being able to carry on production with only minimal interruption.

Clearly, if you are in a risky spot, it pays to be prepared. An emergency plan drawn up by The Gap clothing stores of San Bruno, California, allowed the retailer to get all its San Francisco Bay area outlets back to business three days after the Loma Prieta earthquake struck the region in 1989. Carter Hawley Hale in the mid-1980s took the precaution of having seismic audits done on all of its Broadway department stores in earthquake-prone southern California. The store near Northridge was identified as particularly vulnerable to life-threatening damage and business interruption. When the Northridge earthquake struck, the shear walls that had been added to this store protected it while a neighbouring store collapsed.

The first step in such an audit, says EQE International, is to provide the company with a realistic estimate of how much it stands to lose if the worst happens (the "probable maximum loss"). Next, the study should identify opportunities to reduce the level of loss—say, by strengthening key parts of the building and bracing individual pieces of equipment. The firm then needs to decide on an order of priority for the various measures it might adopt, and implement those that best meet its need for both safety and profit.

When done properly, risk management can save a fortune in insurance premiums, always assuming coverage in seismically active areas can be obtained at all. Many insurance companies are refusing to write earthquake policies these days. Those that still do have doubled their premiums over the past year, reduced the coverage and asked customers to foot a larger share of the bill.

Intel, the world's top semiconductor firm, has its headquarters in Santa Clara, close to the San Andreas fault in Silicon Valley. It now carries no earthquake insurance on its manufacturing plants in such seismically risky locations as California, Puerto Rico, Japan and the Philippines. The company finds it does better by spending the money on building its plants to high standards—often far above the requirements of local earthquake codes—and securely bolting down all the equipment inside. With a contingency plan in place since the mid-1970s, Intel was able to get all bar one of its Santa Clara buildings back into full operation the day after the M6.9 Loma Prieta earthquake in 1989. The cost of the damage and interruption still came to $800,000, but without the precautions it would have been more like $25m.

Shock absorbers

Any number of devices are available to help buildings survive earthquakes. One of the most common types used in steel-framed or reinforced-concrete buildings is a damper unit, similar to a car's shock absorber, that is connected diagonally between adjacent columns throughout the structure. In absorbing the energy of the seismic shock, the dampers generally halve the peak accelerations to which the building is subjected. More often than not that is enough to keep it standing.

Another increasingly popular form of protection is to isolate the building from the ground with fat rubber pads. When the ground starts to move in an earthquake, the pads distort and absorb the deflections, preventing damage to the rest of the building. Fluor Daniel, a large construction company in Irvine, California, has completed a number of these so-called base-isolation buildings, including a command centre for Los Angeles County

Fire Department engineered to withstand earthquakes up to M8.3. To the building's occupants, such a megaquake would feel like a rumble of M5.3.

The fire department's new headquarters, along with dozens of other base-isolation buildings in the Los Angeles area, came through the Northridge earthquake with flying colours. So did two similar buildings in Kobe. But none has yet been subject to a "fatal fling"—a large displacement in one direction and then immediately back again. Tom Heaton of the United States Geological Survey in Pasadena, who found that 20-storey steel-framed buildings could topple when caught by a fling, has also tested base-isolated buildings in his computer model. They smashed into the walls surrounding their foundations and wrecked themselves. ■

Look out for yourself

Time to stop thinking someone else will foot the bill

HOW safe is safe enough? Only the nuclear industry has come close to resolving that, by choosing to build its power stations on land where the probability of a serious earthquake is less than once in 100,000 years. But not everyone needs, or can afford, to be so particular.

So what kind of earthquake frequency might be acceptable for building homes, offices, shopping malls, schools and hospitals? Some people think that once in 1,000 years for a major earthquake on their doorstep is too frequent, even though it is not far from the kind of risk they accept in their daily lives of, say, having a road accident or a heart attack. However, most of the big conurbations throughout the world's seismic belt sit on top of faults capable of generating earthquakes of M7 or more at least once every 100-200 years.

Why do people build their dream homes on a flood plain, along a tornado alley or astride some seismic fault when normally they take great pains to protect themselves, their loved ones and their property? Could it be that they have come to see natural disasters not as capricious acts of God that they endure for personal reasons (employment, good schools, spectacular views), but as problems for governments to resolve?

Certainly, there is a tendency to look to others to shoulder the risk of living in a hazardous place. The growing costs and difficulty of obtaining adequate earthquake insurance in seismically active areas the world over has caused public outrage. "There is a growing perception that earthquake insurance is some kind of right, or entitlement, to be provided by the government or private insurers at a subsidised price," complains Eugene Lecomte, head of the Insurance Institute for Property Loss Reduction in Boston.

Yet insurers find that, given the premiums that home-owners are prepared to pay, they can no longer afford to meet the claims of even a moderate-sized disaster such as last year's Northridge earthquake, let alone the Kobe one earlier this year or some future quake beneath Seattle, Los Angeles or Tokyo. Between 1970 and 1993, the insurance industry in California collected $3.4 billion in earthquake premiums, whereas claims over the period totalled less than $1 billion. Last year, they took in $500m-worth of earthquake premiums and paid out $11.4 billion for property damage caused by the Northridge shock alone. Rather than face further losses, casualty insurers in California—who are legally required to offer disaster coverage if they sell home insurance—are now getting out of the residential business altogether.

The reinsurance market bears part of the blame. In seeking to spread their disaster risks, insurance companies around the world collectively pay about $5 billion a year to Lloyd's of London and other reinsurers. Given the normal odds on disasters, that means the total annual capacity for disaster insurance worldwide can be no more than $50 billion or so. A disaster of Kobe proportions would bankrupt even the biggest insurers in America.

Japanese insurers will survive the Kobe quake because only 3% of home-owners in the disaster area had earthquake coverage (compared with 40% in Los Angeles). Moreover, under Japanese law, the maximum amount insurers have to pay out for property damage on any one earthquake claim is $110,000. All told, last January's disaster will set the Japanese insurance industry back a mere $560m. The bulk of the cost will be borne by 147,000 uninsured homeowners.

Whether adequate earthquake coverage is unavailable because insurance companies are leaving the business or because governments restrict claims to protect the insurers, the effect remains the same. Home-owners have to stop relying on being bailed out after a disaster and start spending money on preventing damage in the first place. They need to copy what companies such as Intel have been doing all along.

A wish list of three

Such a wholesale change in attitudes will not happen overnight, nor without prompting. At least three initiatives are needed to persuade property owners to take the precautions needed to reduce the level of death and destruction the next time a big earthquake strikes an urban area.

First, the concept of earthquake zoning needs redefining. The Uniform Building Code (UBC), updated annually in America and published wordwide every three years, focuses mainly on the safety of a building's occupants and emphasises such factors as resistance to fire and structural failure. The UBC for America contains a map showing the boundaries of six seismic zones based on ground motions and damage patterns from previous earthquakes. The higher the seismic activity, the tougher the building regulations.

But the boundaries are set too broadly and do not attempt to take account of local faults that can generate seismic hot-spots. To be effective, earthquake zoning has to be mapped at the level of individual communities. However, such zoning needs to be implemented by a state or regional authority if the provisions are not to be diluted at local level.

Second, a grading system is needed to assess how well communities actually enforce their building codes, just as the insurance industry in many countries grades communities on their ability to fight fire. Inspectors say the cost of the Northridge quake might have been halved if all the buildings damaged had actually been built to code. In Kobe, inspectors found that few of the traditional houses that collapsed had steel reinforcing T-plates bolted across their post-and-beam joints as required by the building regulations.

The third measure should ensure that efforts are made to protect buildings as well as occupants. Most regions in the seismic belt have a set of official guidelines that tell architects how much damage a building of a certain design is likely to suffer in a given earthquake, and how much roughly it will cost to repair afterwards. The current Californian rule book is called ATC-13, a compendium listing the seismic properties of 78 types of buildings which was developed in 1985. Californians can thank ATC-13 for the excellent life-saving performance of buildings erected in the state in line with its rules over the past decade.

Better overdo it

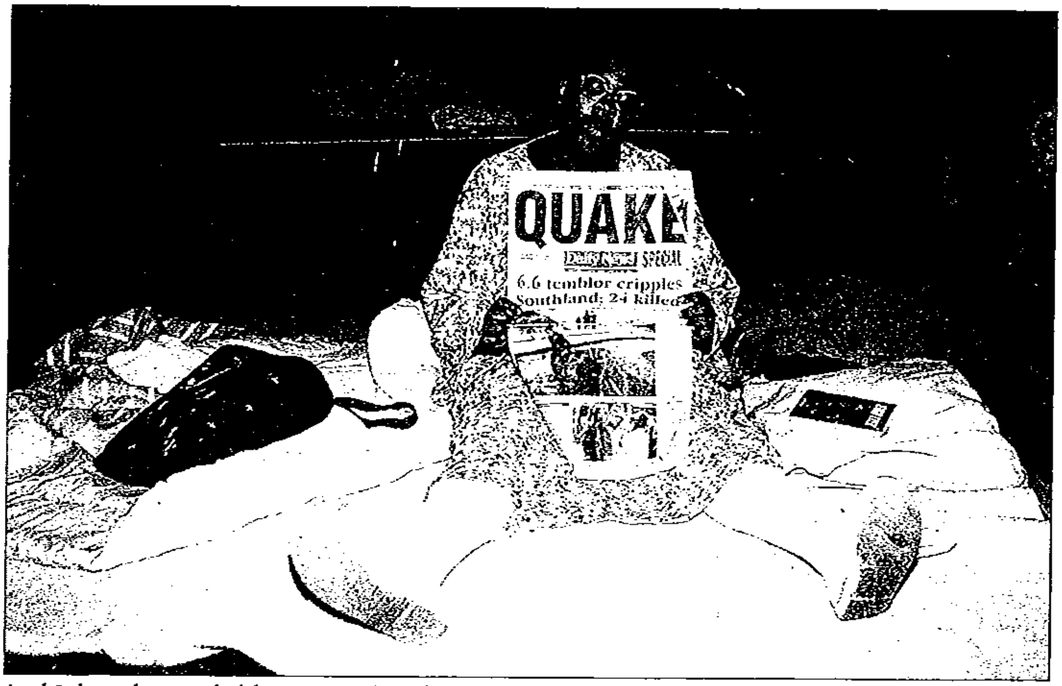
But the guidelines do not go far enough. "We need a way of identifying the [opportunity] cost of just building to code," says William Sherman of Intel. As companies such as Intel have found to their benefit, there can be huge advantages from designing a building "beyond code" when it comes to getting back to work after a big earthquake. Mr Sherman would like to see lower property taxes as well as more modest insurance premiums on buildings constructed to higher standards than the code requires. Conversely, higher property taxes should be charged on buildings likely to be badly damaged in an earthquake. "The tax differential should cover the long-term costs to society of retaining a risky building," says Mr Sherman.

This stick-and-carrot approach can prod property owners into making their buildings safer, and not just brand-new buildings. It is not the clusters of shiny new downtown buildings hurriedly thrown up on flimsy foundations that pose the gravest dangers in the world's earthquake zones, but the fearful legacy of brick and stone and rotten timber from generations ago. The civic piles, Victorian factories and elegant terraces of turn-of-the-century residences are among the most lethal buildings wherever earthquakes strike.

The California Seismic Safety Commission wants to see a five-year crash programme to retrofit all seismically dangerous buildings within the state. In a long-delayed report, the commission will recommend the use of income tax incentives to encourage owners of older urban buildings to upgrade them to modern safety standards. "Accelerated depreciation schedules would be powerful incentives to encourage investment in seismic retrofit," says the unpublished report.

The retrofit improvements range from bolting buildings to their foundations to securing water heaters properly and installing flexible connectors and automatic shut-off values for gas appliances. No attempt is made to quantify the cost. The report merely suggests that the loss of tax revenue from providing the incentives would be offset by the lower costs of recovery after future earthquakes. That may well be true, but in these cash-strapped times it will be a difficult deal to sell.

The conclusion is inescapable: more disasters on the scale of Kobe will happen before we learn at long last to protect ourselves, our buildings and our lifelines properly. The next time a quake of M7 rips through a metropolitan area, it will be the local residents who will have to foot most of the bill, as they did in Kobe. This is the moment for all of us at risk to start looking out for ourselves.



And I thought Northridge was a nice place to live