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The History and Significance of Japanese Earthquake Countermeasures

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Abstract for:

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Japan is well known for its earthquakes; the damage that they cause sometimes makes international headlines, one example being the disaster that occurred on March 11, 2011. Through my research, I found that although Japan has always been plagued by earthquakes, the Japanese government only started to seriously create and enforce building regulations in the past 50 years. Also, there is a clear pattern of revisions and new building codes being added soon after highly destructive earthquakes strike. Since the 2011 Tohoku earthquake no new regulations have been enforced, but researchers are undoubtedly striving to discover new and better earthquake countermeasure technology.

This paper discusses an overall view of the anti-earthquake technologies that Japan already has and how they work, regulations that are in place, differences between small buildings and skyscrapers, as well as new technology and the future of anti-earthquake measures. It also compares and contrasts Japan with other countries that experience regular earthquakes, such as Chile and Mexico, while showcasing the technology and procedures that are unique to Japan.

Although my research focuses on earthquakes, the main topic is people. Anti-earthquake technology is created to save people and is essential in Japan, a country which already has a population crisis and a growing number of elders who may struggle in the event of a natural disaster. With international help, Japan and other earthquake-riddled countries can use technology to become safe countries where no one is fazed – much less afraid of – natural disasters such as earthquakes.

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contrast with Japan's low youth population. The countermeasures that Japan has now are useful and have no doubt saved many lives, but with international help, Japan and other earthquake-riddled countries can become safe countries where no one is fazed – much less afraid of – natural disasters such as earthquakes.

Seismic Waves and Measurement Scales

Before we discuss techniques to reduce the effects of earthquakes, we must first understand how earthquakes are created and how they cause damage to structures. It is common knowledge that earthquakes are created at fault lines, or the places where two tectonic plates meet. Japan and its numerous small islands are situated above four different tectonic plates, and the bedrock of these four plates – the North American plate, the Pacific plate, the Philippine plate, and the Eurasian plate, grouped together as seen in figure 1 -- grinds together at fault lines, usually with one tectonic plate forcing its way underneath another, until it distorts past its limit. The accumulated stress is released, forming seismic waves. An earthquake's strength is calculated by measuring the strength of these waves (Saitou 16).

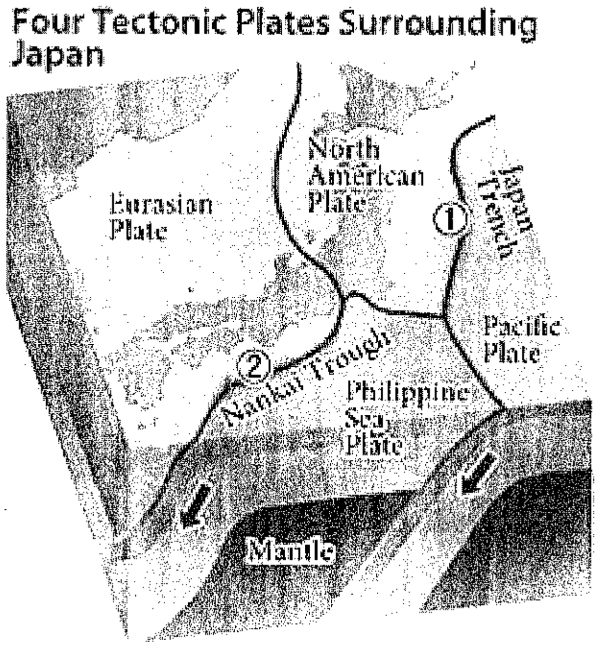

Figure 1

Each earthquake has only one magnitude, which is a numerical representation of the energy at the epicenter of the earthquake. There is no unified international standard of measurement for magnitudes, so caution should be used when comparing them. Although the moment magnitude (M_W) scale is used internationally and the Richter scale is used often in the uses its seismic scale as a warning device (Saitou 24). Although the scale only goes up to number 7, levels 5 and 6 are divided into "weak" and "strong" for a total of 10 levels.

The Shindo Scale (Saitou 25)

Level 0	People don't feel any vibrations
Level 1	People sitting quietly inside a room may feel some slight vibrations
Level 2	A majority of people sitting quietly in a room feel vibrations
Level 3	A majority of people inside of rooms feel vibrations
Level 4	-Most people are surprised -Lamps and other hanging objects sway -Easily moved ornaments may fall over
Level 5 Weak	-A majority of people feel fear and the need to hold onto something -Plates and books that are on shelves may fall - Furniture that isn't fixed to the wall and other unstable objects may move
Level 5 Strong	-Walking is difficult if you don't hold on to something -Many plates or books that are on shelves fall - Furniture that isn't fixed to the wall may fall -Block walls that aren't reinforced may collapse
Level 6 Weak	- It is difficult to stand - Almost all furniture that isn't fixed to the wall will move, and many of them will fall. Sometimes doors cannot be opened -Tiled walls or window glass may shatter and fall -For low wooden buildings with earthquake counter-measures, tiles may fall and the building may tilt or shake
Level 6 Strong	-The only form of movement is crawling. Some people may be sent flying -Almost all furniture that isn't fixed to the wall will move, and many things will fall - Many low wooden buildings with earthquake counter-measures will tilt or shake -Large cracks in the ground may form, and landslides or the collapse of edifices may occur
Level 7	- The tilting and shaking of low wooden buildings with earthquake countermeasures will become even more pronounced -Rarely, tall buildings with counter-measures may tilt -Many objects will fall in low, reinforced-concrete buildings with counter-measures

most valuable research comes from buildings that are still standing after surviving thousands of years of earthquakes.

Historical Engineering

Although engineers nowadays are able to use the laws of physics and mathematics to design structurally sound buildings, the engineers who designed buildings hundreds of years ago were working with almost pure estimation. They had a good grasp on the basics, such as the strength of stone versus the strength of wood, or the importance of a good foundation, but when it came to actually putting everything together, they had to learn from their mistakes. In Europe, it most likely took decades of rebuilding after wars for castle builders to perfect walls that could take a beating from battering rams, arrows, and fire. In Japan, the same process took place with earthquakes instead of man-made destruction. Also, scholars who traveled to China, Korea, and other countries brought back not only tea and cultural customs, but also building technology and architectural styles.

One example of construction that has been shared across Asian borders and is known around the world is that of Asian pagodas. Pagodas can be any number of levels, although they are usually built with an odd number of levels, and look different from country to country. 5-storey pagodas in China and Japan are known for their resilience against earthquakes, as many of them are well over hundreds of years old. The 5-storey pagoda at Toji Temple in Kyoto has burned down multiple times, but has never been destroyed by an earthquake (Why Pagodas Don't Fall Down).

The Toji Temple pagoda was constructed differently from other pagodas around the world, and those slight changes may be what have kept it standing for so long. For example, the overhang on the eaves of the pagoda is much longer than most pagodas. This is to keep rainwater of having the logs in the foundation, the temple has logs in between the stone arches and pillars (Saitou 120). It seems that quake-absorbing and damping technology was the most widely used technology in Europe and the Middle East.

Unfortunately, structures that have stayed standing even until the present do not necessarily have seismic technologies built-in. On April 25, 2015, a 7.8-magnitude earthquake struck and devastated the Kathmandu Valley in Nepal (Gannon). The Kathmandu Valley is the "cultural heart of Nepal" and has seven UNESCO monument zones (Gannon). Although the devastation was horrendous, what was most interesting was that next to a building that had escaped with little or no damage, there would be a pile of rubbish from a completely demolished building. Amongst the rubble were the remains of a fifth-century Buddhist temple and the Dharahara Tower, which had been rebuilt in 1934 after an earthquake damaged the original 1832 structure (Gannon).

Building Design

There are many tricks and additions that engineers can use to reduce the impact of seismic force on a building, but every building's protection always starts with its basic design. Right from the start, decisions on building materials, the amount of space in each room, and how tall the building will be are all crucial to the building's structural stability. Also, the taller the building, the more requirements it has to pass to receive approval for its construction (Vastag). Finally, the structure's location should be taken into account.

At the most basic level, architects and engineers in earthquake-prone areas tend to design symmetrical buildings with few ornaments. This is because asymmetrical buildings are weak along their longitudinal axis and may break apart when stress is focused along that line. Also, the buildings in Japan have been required to have an earthquake-resistant structure (Real Estate Tokyo). These structures can be anything from simple trusses, which are inserted to strengthen wall frames and are found in most buildings, to moment-resisting frames or base isolation systems.

Of course, the size and height of a building determine what sorts of technology should be used to strengthen it. Short buildings (anything less than three stories) are only required to have reinforced walls and particularly thick foundations. Mid-rise buildings, which are classified as being up to 100 feet tall and include hospitals or office buildings, sometimes have rubber or fluid-filled shock absorbers installed in the foundation. These shock absorbers move side to side when an earthquake hits, dissipating the lateral motion of the shock waves (Vastag). Another option for mid-rise buildings is to use base isolation systems. Base isolation systems "[float] a building above its foundation on a system of bearings, springs, or padded cylinders" (Harris). Base isolation systems allow the foundation to move without upsetting the structure above it.

Skyscrapers and high-rise structures are without a doubt the most challenging structures for engineers to design. Many taller buildings use a mixture of techniques for shorter buildings, but sometimes extra protection is needed. One of the most commonly used techniques is that of damping systems. Damping systems can either use liquid or a heavy mass, and unlike shock absorbers, they are placed at the top of a building instead of in the foundation. When the building begins to vibrate due to seismic waves, the mass rotates in the opposite direction and reduces the amplification of the seismic vibrations (Harris).

Tokyo Sky Tree, which was completed in 2012 and is the tallest tower in Japan at 634 meters, uses both solid and liquid mass damping systems. The concrete tower at its core doubles as a modern *shinbashira* – much like with the historical pagodas, the column is structurally

Regulations for Buildings

Building regulations are spelled out in a country's building codes. Building codes are defined as a "set of minimum regulations intended to safeguard public health, safety, and [the] general welfare of the occupants" (Moehle). Each country takes a different approach to the creation and enforcement of its building codes. Some countries have codes created by government agencies and enforced nationwide, whereas other countries give local jurisdictions the authority to create and enforce their own building codes (Moehle). For example, municipalities in Tokyo and Shizuoka have established their own guidelines for public buildings such as schools, hospitals, and libraries. Also, metropolitan areas usually have higher standards than other areas in order to guarantee urban functions in the event of a natural disaster (Saitou 74).

Before 1919, Japan did not have a uniform building code. Even after its creation, the code only placed height limits on buildings, a code which was abolished in 1970. The first provision for earthquake-protection in urban building codes was added in 1924, a year after the Great Kanto earthquake (Saitou 64). In fact, almost every major earthquake has caused the Japanese government to reevaluate its building regulations. Despite that, no new provisions have been added since the 2011 Tohoku earthquake, by far the strongest and most destructive earthquake in Japan's history. However, this may be because the more immediate devastation was caused by the tsunami and the danger created by the nuclear power plant in Fukushima, not by secondhand damage from the earthquake itself.

Most of the property damage and loss of life caused by the Great Kanto Earthquake was also not from the earthquake itself, but from the fires that raged throughout Tokyo. Out of 105,000 dead or missing, it is said that about 90,000 people passed away from fire-related causes, a percentage exponentially higher than those who were crushed to death (Saitou 62).

users and architects, as well as a more precise method for architects. For all three methods, if the value is less than 1.0 the building is considered to be in danger of collapse in the event of an earthquake (Saitou). Buildings that were built before 1981 did not have to follow diagnostic measures or measure for horizontal seismic intensity ratios or worry about I_S , so very few of them have earthquake countermeasures. Such buildings are classified as "existing ineligible buildings" (Saitou 70).

You may be asking, ineligible for what? In June 1995, the Earthquake Disaster Special Measures Law established a state aid rate to renovate and strengthen public elementary and middle schools. Using these subsidies and the seismic diagnoses for renovations, Japan's public schools have become much safer. Also, in December of the same year the Seismic Refurbishment Promotion Act targeted unsatisfactory standards in schools, elderly homes, hospitals, department stores, and other public, large-scale buildings. Included in this list are buildings that handle hazardous materials as well as homes or buildings that, if they collapsed, could block evacuation routes (Saitou 70). The Seismic Refurbishment Promotion Act has provided subsidies, grants, low interest rates and tax reduction on loans and financing plans used to renovate and refurbish such buildings, all of which are considered "specified designated buildings" (Saitou 70).

In Japan, it is not rare to tear down a house and build a new one every 50 years, rather than just remodeling or fixing problems in the old house. However, when constructing a new building, the evaluation process is fairly different. Before construction begins, design plans for the new house must be submitted to a specific housing performance evaluation institution. This evaluation institution is a trustworthy third party so future homeowners can be sure that their home plans are truly up to code and the builders are following regulations. After the designs are frames rock up and down, directing energy down towards a fitting in the foundation that has many steel tooth-like fuses. The fuses smash together, and once the earthquake is over the steel cables pull the structure back into place. The fuses, rather than the structure itself, may break and quickly be replaced by workers (Harris).

While this works as a quick fix to keep construction costs for the actual building low after an earthquake, the cost of labor and replacement fuses could rise quickly. Assuming that fuses break every time there is an earthquake and that multiple fuses break every time, the cost of upkeep could exceed the cost of installation in just a few years, especially in Japan where earthquakes happen almost daily. Then there is the issue of all the used fuses, and whether or not they can be recycled and reused. Finally, because the building is allowed to shake without breaking, the things inside of it also shake. With no stabilization, everyday objects in the home can become deadly weapons in the event of an earthquake. The rocking frame protects of the shape of a structure, but just the shape is not enough.

Another technique, called the seismic invisibility cloak, uses plastic rings to make a structure "invisible" to seismic waves. The plastic rings are buried concentrically under the foundation of the structure and are compressed when they are struck by the waves. The rings guide the energy of the waves to exit through the other side of the rings without disturbing the foundation above (Harris).

This technique was first tested back in 2013 by a team of French engineers and ground specialists. However, their test hypothesis was slightly different. The test was done in a sedimentary river basin in Southern France. As mentioned earlier in this paper, sandy soil and sedimentary basins can amplify seismic waves. Rather than using springs that passed the seismic energy along through and out the opposite side, these researchers decided to dig vertical columns in a pattern in their test area, creating voids. These voids later reflected the manmade waves sent out of three earthquake-shaking dimensions, and it would not protect a house against an earthquake that rises more than three centimeters. In fact, it is almost more dangerous to have a house unattached to its foundation, as it could slip right off in the event of a tall earthquake wave or tsunami (Abrams). Also, some earthquakes have their biggest tremors at the beginning of the quake, and by the time the airbag is fully inflated it may be "pushing up against the rubble of an already damaged house" (Abrams).

That being said, by the end of 2012 close to 100 homes had already been retrofitted with Air Danshin's system. It is unknown how many are now in use, or how well the system has protected those homes from damage (Abrams). The system costs three million yen (approximately $28,000 at the current exchange rate) and may be considered a worthy investment to those who seek to protect their home. After all, $28,000 is a small price to pay to protect a home many years. The only question is how much are homeowners willing to pay to protect their investment? One tenth of the total cost of the house? Half of the total cost? Homeowners who are willing to spend $800,000 or more for the luxury home of their dreams might see $28,000 as small change, but others may be hesitant to invest that much in technology that has not yet been scientifically proven.

Competing against Air Danshin's system is the latest base isolation system from California-based company Arx Pax. The company, which is known for its Hendo Hoverboard, has designed a three-part building foundation system that uses magnetic-field architecture to float an entire structure off its foundation after a queue from the U.S. Geological Survey's ShakeAlert system (Terdiman). Ark Pax's CEO even boasted that the hover system only needs "one second [of warning]," a time which very well may beat Air Danshin's bulky airbag design (Terdiman).

money to actually build a working prototype, and that means the world may not see this technology in action for quite some time.

Predicting the Next Big Earthquake

One of the most important counter-measures against earthquakes is knowing when they will come. Even just a few seconds of prior notice gives someone the time to turn off his or her stove or heater, which can reduce the risk of a house-fire. In fact, the secondary destruction that comes from earthquakes – such as destruction caused by fire or tsunamis – can take more lives than the event of the earthquake itself. Currently, the Japanese Meteorological Agency is able to send out an emergency message to receiving terminals with the exact location and time of Shindo level 3 or larger earthquake within a minute and a half of its occurrence. Emergency messages are sent out by television, radio, cellphone messages, and are made available on the Internet whenever a Shindo 5 (weak) level or higher earthquake has been detected (Saitou 24).

These emergency messages are sent out by the Japanese Meteorological Agency after their observation networks have recorded hits on two or more seismographs. There are many different kinds of seismographs and each has a specific purpose, so researchers cannot rely on just one machine. For example, a broadband seismometer is able to capture slow earthquake vibrations and analyze the Earth's interior structure, but it cannot measure strong vibrations. That is why researchers also use a strong-motion seismometer, which does what a broadband seismometer cannot. When these systems are added together with a seismic calculator function and a recording device, they become proper seismographs (Saitou 26). Funnily enough, the seismograph was invented by a Japanese man, Dr. Kyoji Suehiro, but was first tested in California when Suehiro was invited to America to give a lecture (Saitou 50).

The Meteorological Agency has a wide range of sensors covering just the area that researchers believe will be affected most by the Tokai earthquake when it hits. Any time sensors in and around this area detect seismic vibrations, changes in the frequencies are observed. If the deformation is fairly far away from the Tokai area and the changes are accompanied by multiple low-intensity earthquakes in that area, it can be assumed that the anomaly has no relation with the Tokai earthquake. In 2004 and 2005, researchers had to deal with many false hits in the Tokai area, which caused many tense months of close observation (Hoshiba).

Because it is imminent and predicted to cause destruction on par with the Tohoku earthquake (around magnitude 9.0), the Tokai earthquake has its own alert system, and even has its own page on the JMA website. A Tokai earthquake report is issued if significant changes are detected by at least one sensor in the Tokai area, or if notable activity has occurred in the source region, but the information cannot be evaluated immediately. An advisory is issued when the same seismic activity has been evaluated and regarded as "enhanced," which means the seismic activity may or may not be a precursor to the Tokai earthquake. Finally, a warning is sent out when the significant changes in seismic activity are reported at three or more sensors in the Tokai region and the Tokai earthquake is about to occur soon (Hoshiba).

Societal Reactions to Natural Disasters

When even the most modern, expensive technology fails, humans are left to rely on themselves and help from others. Natural disasters shake societies in multiple ways, but there are also multiple ways for people to help rebuild afterwards. This was especially true for Japanese architects, who felt pressure to change after the disastrous events of the 3/11 Tohoku earthquake. Before, architects were viewed only as "[designers of] special flamboyant buildings," not so much designers for emergency structures or advocates of strength and safety (Tamashige).

of 2011 related to disaster rescue law, emergency preparedness, food sanitation regulation, and victim support (Umeda). These laws and the changes that came from them were not meant to just help the victims of the earthquake and tsunami, either. They are laws that protect all of Japan's residents, especially the laws regarding close watch over the amount of radioactivity found in Japan's food products and the laws that equate to better preparedness for the next earthquake, no matter where it may strike.

International Cooperation

Japan was not the first country to suffer from a natural disaster, and it will not be the last. After natural disasters, aid and resources are quick to come from overseas. However, there are times that material resources are not the only resources that are needed. The idea that countries should band together and share educational and research resources was one of the main points for the creation of JICA, an international seismic training program.

Started in 1977, the five-week program lectures trainees from developing countries such as Algeria, El Salvador, Haiti, and Thailand, on earthquake and tsunami mechanisms as well as earthquake-resistant technology. The students are invited to Japan, where they are taught the material and then shown examples of the technology in various buildings and universities (JICA's World). The Building Research Institute's International Institute of Seismology and Earthquake Engineering also has a similar international training program that has been around since 1962, with more than 1500 trainees visiting from 50 countries (Saitou 152).

The JICA program and other similar training programs allow Japan to share its knowledge and technology with students in other countries, but the sharing is a one-way street where the students receive knowledge and then take that knowledge back to their own countries. While it is important to pass down information to those who did not have it before, it is also

Japanese politicians work hard to solve Japan's internal problems, but natural disasters are not only Japan's problem. They are a global problem, and international aid should not just be limited to donations of money, food, etc. In the 1990s, Japan was the world's largest contributor to official development assistance, through post-war reparations and peace contributions. However, economic difficulties cause the amount of ODA in Japan's budget to be reduced each year (Saitou). Training programs such as JICA are a good beginning, but the switch from monetary assistance to technology assistance may be slow in coming. Not that they should be treated as simple assistance – international cooperation requires constant communication, not just communication during a rebuild period.

Just as each earthquake is unique and constantly changing, our reactions to earthquakes must also be fluid. When the procedures for natural disasters become static, or when we stop trying to learn from what has occurred, we leave holes in our defenses. That does not mean that we can only learn from our experiences, however. Even in periods of peace, we must work hard to think outside the box and predict what may occur. Only by being prepared ahead of time can we reduce damage before it can occur. Finally, we must not be stingy with our knowledge, and share it in the hopes of creating international alliances. The insights and assistance from others have never proven to be more trouble than they are worth.

businessinsider.com/earthquake-resistant-buildings-2011-3#ixzz3kcHWi9zs>.

Moehle, Jack. "Seismic Design and Performance Verification." Seismic Design of Reinforced Concrete Buildings. McGraw-Hill Education, 2015. Access Engineering. Web. 02 Sept. 2015.

Saitou, Taiki. "Jishin to tatemono no hon." Tokyo: Nikkan Kogyo Shimbun, Ltd., 2013. Print.

Tamashige, Sachiko. "Building social change after the earthquake." 30 Jan. 2015. The Japan Times. 08 June 2015. <http://www.japantimes.co.jp/life/2015/01/30/style/building-social-change-earthquake/#.VXVkkGSeDGc>.

Terdiman, Daniel. "New Technology Claims It Can "Hover" Buildings Before Earthquakes." Fast Company. 04 June 2015. Web. 10 Apr. 2016.

"Tokyo Sky Tree." Architecture of the World. 30 Dec. 2014. Web. 10 Apr. 2016. <https://en.wikiarquitectura.com/index.php/Tokyo_Sky_Tree>.

Umeda, Sayuri. "Japan: Legal Responses to the Great East Japan Earthquake of 2011." The Library of Congress. Sept. 2013. Web. 10 Apr. 2016. <http://www.loc.gov/law/help/japan-earthquake/>.

Vance, Erik. "Earthquake tests 25 years of Mexican engineering." 22 March 2012. Nature.com. 02 Sept. 2015 <http://www.nature.com/news/earthquake-tests-25-years-of-mexican-engineering-1.10291>.

Vastag, Brian. "Japan a leader in engineering earthquake-proof structures, helping to limit damage." 11 March 2011. Washington Post. 02 Sept. 2015. <http://www.washingtonpost.com/wp-dyn/content/article/2011/03/11/AR2011031104541.html>.

"Why Pagodas Don't Fall down." The Economist. 20 Dec. 1997. Web. 18 Jan. 2016. <http://www.economist.com/node/456070>.

because the Japanese islands, unlike any other place on Earth, are situated above 4 tectonic plates that are constantly colliding. Amongst sinking deep sea plates are trenches, and trenches that are less than 6000 meters deep are called troughs. To the east of the Japanese islands is the Japan Trench, and to the south is the Nankai Trough.

#5 Periodically Repeating Earthquakes

Once the bedrock distorts past its limit, the surfaces of the faults crash together and an earthquake occurs. After that, there is a tranquil period until the distortions once more accumulate. Whenever there is an earthquake fault lines come out of alignment, therefore the relationship between time and how far the gap has widened increases in stair-like increments on an expanding graph. The graph's average trend is called the average displacement rate, and depending on their level of activity active faults are sorted into AA, A, B, and C classes.

Awaji Island's Nojima Fault is B-class (with an average displacement rate of 1 meter every thousand years), and in 1995 in the southern part of Hyougo prefecture an earthquake occurred which caused the fault to slip about 1.5 meters, a distance which had not happened since 1500 years before then. Japan's inland has no AA-class active faults, but about 100 A-class, about 750 B-class, and about 450 C-class active faults have been confirmed. Because it is difficult to confirm the existence of C-class active faults, it is thought that the number is actually much higher.

The Philippine Sea Plate sinks into the Nankai Trough several centimeters each year, and most of that movement is caused by fault slippage, so the Nankai Trough's active fault line is classified as a high AA-class. The faults from previous earthquakes in the eastern sea, widely utilized. The southern part of Hyougo prefecture's 1995 earthquake had an M_J magnitude of 7.3, but an M_W magnitude of 6.9. A magnitude will be unique according to the definition used, so caution is needed when comparing them. Moment magnitude better shows the scale of larger earthquakes, so its 9.0 is used for the 2011 Tohoku-Pacific Ocean Earthquake (Great East Japan Earthquake).

An earthquake's energy is proportionate to the fault area multiplied by the amount of slippage. If the magnitude goes up 1.0 the energy goes up about 30 times, and the fault's length goes up approximately 3 times (area by 10 times, length by 3 times) proportionately. A magnitude 5 earthquake's fault is usually about 4 km long, so using this proportion a magnitude 6 earthquake's fault will be 12 km long, magnitude 7 would be 40 km long, magnitude 8 would be 120 km and so on. The magnitude 9.0 Tohoku Earthquake had a fault length of 500 km. The largest earthquake observed to this day occurred in 1960 in Chile, with a magnitude of 9.5 and a fault length of approx. 800 km.

#7 Japan-Specific Shindo Scale Quick Report

Currently, The Japanese Meteorological Agency is able to make a prompt report on the location and exact time a level 3 or larger earthquake was observed, within roughly a minute and a half of its occurrence. What supports the quick report system are approx. 4300 towers (as of Aug. 2011) stretching across the entire country, an observation network made up of seismographs. The seismographs are set up so that when an earthquake occurs, the scale of the earthquake is automatically recorded and sent to the Meteorological Agency.

The Shindo scale goes from level 0 to level 7, but levels 5 and 6 are further separated by "weak" and "strong" for a total of 10 levels. Phenomenon and damages that usually occur when

The Shindo Scale

Level 0	People don't feel any vibrations
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Level 6 Weak	- It is difficult to stand - Almost all furniture that isn't fixed to the wall will move, and many of them will fall. Sometimes doors cannot be opened -Tiled walls or window glass may shatter and fall -For low wooden buildings with earthquake counter-measures, tiles may fall and the building may tilt or shake
Level 6 Strong	-The only form of movement is crawling. Some people may be sent flying -Almost all furniture that isn't fixed to the wall will move, and many things will fall - Many low wooden buildings with earthquake counter-measures will tilt or shake -Large cracks in the ground may form, and landslides or the collapse of edifices may occur
Level 7	- The tilting and shaking of low wooden buildings with earthquake countermeasures will become even more pronounced -Rarely, tall buildings with counter-measures may tilt -Many objects will fall in low, reinforced-concrete buildings with counter-measures

technologies, such as base-isolation and damping control have become widespread after affirmation of their effects through measuring the vibrations of buildings. It was revealed that the Tohoku earthquake vibrations traveled very far from the epicenter to high-rises in Osaka, where a strong-motion seismograph clearly recorded vibrations moving the high-rises close to 3 meters in each direction. It is thought that Osaka's sedimentary basin was the cause of the lengthy earthquake movements.

Unfortunately, compared to the surface of the earth, buildings are far from having satisfactory observation points or documentation. Looking at observation records comes in use when judging how wholesome buildings are and when adopting evacuation instructions. Hopefully, severe earthquake observations will continue to be developed and improved upon in the future.

#11 Knowing Before the Tremors: Emergency Earthquake Announcement

The waves that are created by fault line collisions are transmitted through the earth's crust as P waves and S waves. Their velocities are about 7 km/second for P waves and 4 km/second for S waves. For example, to reach a building that is 140 km away from the epicenter of an earthquake, P waves would take 20 seconds and S waves would take 35 seconds, for a difference of 15 seconds. Ordinarily, earthquake damage is brought about by S wave tremors principle, so if there is an official notice after P waves are detected there is a small amount of time before the S waves arrive within which counter-measures can be enacted. For example, in a law that was amended in September of 2008 (the Enforcement Ordinance of Construction Standard Law), new regulations stated that all elevators must be equipped with P waves sensors

#13 Acceleration and the Force of Inertia

When the earth's surface vibrates due to an earthquake, buildings have a much larger mass than humans so they also have much more inertia to work with. In other words, the reason why buildings break from earthquake tremors even though people are completely fine is because buildings cannot completely support and protect themselves from the force of inertia. Generally, buildings are constructed to be strong upwards and downwards to protect them from gravity, but they are weak when it comes to left and right inertia created by an earthquake. In particular, masonry buildings made out of brick or stone are very brittle and will collapse in the event of an earthquake.

#14 A Building's Cycle and Resonance

A tall building or a short building, which is safer against earthquakes? If you think in terms of inertia from the earthquake's vibrations, you might think that a tall building with a large mass is at a disadvantage. However, inertia is a product of mass and acceleration, so you must also take into account the amount of acceleration that occurs according to the how much the building is shaking.

The time a tremor takes is called its cycle, and the cycle of the tremors characteristic to the plank is called its natural period. If the plank has similar tremor cycles as its own natural period, it will react and large tremors will begin. This phenomenon is called resonance. If the plank's cycle and natural period match, inertial force and timing work together so that the plank's rebound movements accelerate, magnifying the tremors little by little. This is the structure of the resonance phenomenon.

#16 The Ruler Experiment (2)

Let's think about the model of the building with a weight and spring attached to the upper half. The heaviness of the weight is much lighter than the building's own weight, and we have matched the strength of the spring to be the same as the natural period of the building and the natural period of the weight. By drawing the resonant curves for the situations in which the weight is fixed and when it is moving, you can see that the mountains on the graph when the weight is fixed become a valley when the weight is moving because the tremors are being suppressed. This is the fundamental principle of the TMD (Tuned Mass Damper) vibration control system. As the weight gets lighter, the interval between the 2 mountains on the resonance curve becomes narrower and the controlling system becomes less effective. On the other hand, if the weight is too heavy it becomes difficult to control the weight's own vibrations.

TMD is implemented in skyscrapers, towers, and other tall buildings, and the weight is usually equal to about 1% of the building's weight.

#19 Ground Motion's Response Spectrum

In order to record strong ground motion that causes damage in buildings, a special seismometer called a seismograph is needed. In 1931, Dr. Kyoji Suehiro was invited to America to advocate his observations using the seismograph, and America began to use the seismograph before it was implemented in Japan. The first strong motions records were of the Imperial Valley earthquake in California, America (1940, M7.1) and were recorded by the El Centro substation. Even today they are used as standard strong motions records for seismic design. We will use the North-South component of the acceleration records and the vibration equation to find the vibration of the building.

stratum, which was formed by sedimentation from rivers and reclaimed land. It has thick deposits in places that used to be bays or parts of the ocean.

For example, the subsurface layer of Tokyo's gulf region is more than 50 meters thick. In order to support high-rise buildings, many stakes need to be driven down to the engineering base in order to support high-rise buildings.

On the other hand, high-rise buildings are often constructed in West-Shinjuku and other places where the subsurface layer is very shallow, and their foundations are placed above the engineering foundation at a depth of about 10~15 meters. They have direct foundations without any pillars, but because it is ensured that the foundation size and embedment depth are sufficient, the building will not collapse during an earthquake.

The ground, much like buildings, also has an easily quake-able natural period, and you can calculate the primary natural period T with the formula $T=4H/V$, where V is the ground's average shear wave velocity and H is the thickness of the ground, also equal to 1/4 of the wavelength. Comparing the vibrations of Eo from a rocky outcrop in the engineering foundation to the vibrations of Es above the subsurface layer, the vibrations of the primary natural period are magnified 2~5 times. The amplification rate is proportionate to the reciprocal of the earth layer's impedance ratio (density X the shear wave velocity ratio). In other words, the softer the earth layers are, the bigger the waves are. The reason that damage caused to housing during earthquakes is concentrated around areas of soft ground is because of this.

#22 Ground Liquefaction and Counter-Measures

When sandy ground receives the vibrations from an earthquake it loses strength and becomes like a liquid, and the muddy ground or the phenomenon of water spouting is called

Column

After receiving very enthusiastic cooperation from a residents' association, I gave a lecture at a high-rise mansion. I received structural calculation documents beforehand, so after a brief explanation on earthquake countermeasures for mansions, I reproduced the vibrations of buildings based on records from the 2011 Tohoku earthquake, which had been observed nearby. The size of the vibrations had almost no effect upon the safety of the buildings, but it seemed that the residents' bodily experiences made the vibrations seem larger than they actually were.

In addition, I also forecasted the seismic waves that may come from an earthquake located directly underneath the capital, which may occur in the future. All of the residents were brimming with curiosity as to what would happen to the floor that they were living on under such circumstances. The results found that although some cracks may be formed in the building, it would not collapse. Of course, I explained that the calculations were only an example, and that in a real earthquake the results might come out differently. After the lecture, an elderly woman living in the high-rise thanked me because after the Tohoku earthquake she was so troubled by fear that she felt vertigo and was taken to a hospital, but she felt relief after listening to my lecture. I also received many positive opinions on the feeling of having to keep water and emergency food stores handy. On the other hand, there were many people who were concerned that the asset value of their mansion would go down after an earthquake.

This lecture was an attempt by specialists to encourage residents' self-help efforts. Above all, in the act of showing an animation of a mansion swaying due to an earthquake, I could see the change of the audience's mindset of how other people's problems will also become their problems.

both earthquake and fire-resistant, jumped to the forefront as a building material in urban area city buildings.

There is structural technology that was born in Japan and had the opportunity to spread due to the Great Kanto Earthquake. At that time, it was common to use the American way of using bricks in curtain walls (walls where there is no burden on endurance) for reinforced concrete or steel frame construction, and even steel frames were fireproofed with brick. During that time, Dr. Tachu Naito created shear walls by placing the bricks of curtain walls in reinforced concrete and devised steel rebar concrete by using a fireproof steel frame in reinforced concrete, a technique which was adopted by the head office of the Industrial Bank of Japan in Marunouchi, Tokyo. From the building's completion barely 3 months passed before the Great Kanto Earthquake occurred, but the building took barely any damage. It is said that the shear wall idea came from the partition in a trunk Naito was using while he was studying abroad in America. Because of his work on Tokyo Tower, Osaka's Tsutenkaku, as well as many other steel towers, Dr. Naito is also known as Dr. Tower.

#25 The Advance of Seismic Design

The first provision for earthquake-protection was added to building design methods (urban building codes) a year after the Great Kanto earthquake. The content of the provision is based on Dr. Toshikata Sano's thesis "Earthquake-Resistant Structure of Houses." Dr. Sano proposed a seismic intensity method that substituted seismic intensity with a static horizontal force and represented the ratio of the force (horizontal seismic intensity) and the building's weight. It should be noted that the seismic scale being used here is not the same as JMA's Shindo scale.

1891 – Nobi earthquake M8.0, brick damage, about 7,300 victims	1919 – Enactment of the city building method -Building height limit of 100 ft (about 30m)
1923 – Great Kanto earthquake M7.9, major fires, about 105,000 victims	1924 – Seismic provisions added to the city building method -Horizontal seismic force 0.1, safety ratio 3
	1950 – Enactment of the Building Standards Law -Long-term load (such as its own weight) and short-term load (such as seismic force) -Horizontal seismic force 0.2, safety ratio 1.5
1964 – Niigata earthquake M7.5, liquefaction damage 1968 Tokachi-oki earthquake M7.9, shear fracture of the RC short column	1970 – Height limit on buildings is abolished 1971 – Architectural Institute of Japan revised RC criteria -Prevention of shear fractures in RC columns
1978 Miyagi-oki earthquake M7.4, urban damage, twist damage of buildings	1981 – Building Standards Law Enforcement Act (seismic) revision -Primary: standard shear force is approx. 0.2 -Secondary: standard shear force is approx. 1.0 -Rigidity ratio ・ eccentricity ratio
1995 Kobe earthquake M7.3, houses collapsed, about 6,400 victims	1995 – Seismic Refurbishment Promotion Act 1998 – Standard Buildings Law Performance Provision -Limit strength calculation, building certification open to the public 2000 – Housing Quality Confirmation Law (Housing Performance Display System)
2005 Revelation of the Seismic Falsification Problem	2007 – Building Standards Law revision -Structural calculation compatibility judgment system, stricter examinations
2011 Tohoku earthquake 9.0, tsunami damage, about 19,000 victims	

inspection, by using the calculation route, it is necessary to submit the structural calculation compatibility judgment system to confirm the correctness of the structural calculations and the certification from the minister provided by the specialist committee.

In this way, there are various seismic designs that range from Type 4 buildings that are left to the architect's judgment, the "Route 1" of rigid structures, resistance via the strength of "Route 2" buildings, and "Route 3" buildings that even if they are broken in a major earthquake are expected to be tough.

#27 Lessons from the Great Hanshin-Awaji Earthquake

Let us look at a graph of all the main damage from earthquakes that occurred after the 1923 Great Kanto Earthquake. From it we can see that not only the collapse of buildings, but also the fires, landslides, and the tsunami that accompanied the earthquake also caused victims to lose their lives. It also seems that right after the 1948 Fukui Earthquake, the number of deaths due to house collapse decreased. Also, the majority of damage-causing earthquakes occurred in Eastern Japan. Due to the fact that Western Japan has more typhoons than earthquakes, old houses there were built with heavy clay-thatched roof tiles but did not have braces.

During such a time, the Kobe Earthquake occurred at 5:46 PM on January 17, 1995. This earthquake caused the deaths of over 6,400 people, including earthquake-related deaths, and over 100,000 houses collapsed. Wooden houses without braces had heavy roofs that could not resist the earthquake's inertial force, and therefore collapsed fragilely at the time of the earthquake. We found that many of those who lost their lives were under beams and suffered close to instant deaths. It can be said that the quality of the buildings' earthquake-resistant features is what determined their lives.

seismic retrofitting existing ineligible buildings that had taken damage in the Hanshin-Awaji earthquake. The Seismic Refurbishment Promotion Act targets currently unsatisfactory earthquake-resistant standards in schools, elderly homes, hospitals, department stores and other large-scale buildings that large populations use, buildings that handle hazardous material, as well as buildings that, if they collapsed in an earthquake, could possibly block evacuation routes or emergency transport roads. All of these together are called "specified designated buildings." Thanks to this law great measures have been taken to provide subsidies, grants, financing plans with low interest rates, and tax reduction on loans for the seismic diagnosis and refurbishment of specified designated buildings. Also, local governments are required to develop a Seismic Refurbishment Promotion Plan and provide guidance for the owners of specified designated houses.

In June 1995 the Earthquake Disaster Special Measures Law was enforced to establish a state aid rate of renovation and seismic strengthening for public elementary and middle schools. The subsidy rate was raised in the wake of the 2008 Sichuan Earthquake in China where many schools collapsed, and it was decided that 2/3 of the costs of seismic strengthening and 1/2 of the costs of renovation would be paid for by the country.

Detached houses are not the targets of this law unless they are in danger of blocking roads, but many municipalities are implementing subsidies for seismic diagnosis and renovations.

#29 A Building's Seismic Diagnosis

In the wake of the Hanshin-Awaji earthquake, buildings' seismic diagnosis and earthquake-resistance renovations are continuing across the country. In order to understand the way a building's seismic diagnosis is formed, we must pay attention to the relationship between diagnostic method for architects for a total of 3 methods. In all of the methods, if the value falls below 1.0 the building is in danger of collapsing in the event of a large earthquake.

#30 The Differences in Earthquake-resistance According to a Building's Use and Importance

Many government buildings are expected to function as disaster-prevention facilities in the event of an earthquake disaster. Because of that, seismic force multiplied by the component importance factor of 1.5 for I-type facilities (the cabinet office, fire and disaster management agencies, etc.), 1.25 for II-type agencies (Meteorological Agency, Port and Harbor Office), and 1.0 for III-type facilities (public office facilities outside of types I and II) are utilized.

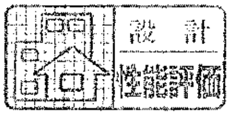
In addition, municipalities such as Tokyo and Shizuoka Prefecture have been establishing their own original guidelines for the component importance factor specifically for buildings of a higher public nature, such as schools, hospitals, and libraries. In particular Shizuoka Prefecture, which is in danger of the future Tokai earthquake, has a seismic zoning coefficient of 1.2 in addition to the component importance factor.

In most countries around the world, the component importance factor has been included in seismic provisions from the start. Also, in China's seismic provisions Beijing, Shanghai, and other metropolitans have higher standards than other areas, from the point of view of guaranteeing urban functions.

#38 Knowing Your Own House's Earthquake-proof Performance

When choosing your home, what kind of quality performance did you consider? You probably realized that you could only say, "I'm sure it's probably safe," with a degree of buyers. Furthermore, if the seismic grade is high you may have the advantage of receiving a discount on earthquake insurance.

Housing Performance Indication System Marks Placed on Evaluation Documents



For Housing Design Performance Evaluation use

For Housing Performance Evaluation (new housing) use

For Housing Design Performance Evaluation (existing housing) use

#42 Mechanisms of Earthquake-resistant Structures

There are various types of structures for buildings to protect against earthquakes, such as earthquake-resistant structures, quake-absorbing structures, damping structures, etc. Quake-absorbing structures and damping structures are structures that use special devices, but you can think of earthquake-resistant structures as "general building structures that were devised to withstand earthquakes." The content of the scheme is unlimited, from the structural format of the entire house down to the details of each material. Such a scheme has been cultivated by repeated experiences of earthquake damage and many years of research. Here, let's introduce a few examples of ways to affect a building's structural format.

A building's structural format can roughly be divided into ways that combine pillars or beams (wire rods) and ways that make the walls the main component of the structure. We will demonstrate when wire rods are the main component of the structure by using matchsticks. If you just stack the matchsticks on each other, the scaffold will fall apart and collapse with an earthquake's vibrations. If you properly bond the matchsticks into a frame configuration (Ramen

Traditional wooden houses have two kinds of foundations -- one where pillars are buried in the ground and one where they are placed above the foundation stone. Placing the pillars above the foundation stone prevents corrosion, and if they are above the foundation stone it is expected that the building will shift and the vibrations will be reduced due to a seismic isolation effect. Nowadays, it is a requirement that a wooden house's construction foundation be bound to its earthen foundation. It is to prevent houses from being sent flying, but it's unfortunate that the seismic isolation effect is lost. It is said that the penetration structure, another building method in which horizontal rungs pierce pillars, has much plastic deformability and can persistently resist earthquakes. Also, Kyoto's Sanjūsangen-dō uses a method called "rammed earth" in which sand and clay stratify and pile up. It has been explained as a seismic isolation method that absorbs an earthquake's vibrations, but that has not been scientifically verified.

Now let's turn our attention overseas. In the north of Iran, which is know for earthquakes, there are stilt houses which have logs slotted together vertically and horizontally in the foundation. It is said that this construction method dates back hundreds of years, and it is said that during an earthquake the logs will roll and the building's vibrations will be reduced, so it is a fine quake-absorption structure. A similar scheme is in another earthquake country, Algeria. There is an 18th century temple in the old urban area of Casbah, in the capital of Algiers, which has logs slotted in between the stone arch and its pillars in order to decrease seismic force.

The people who came before us left wisdom and schematics in the traditional architecture of the buildings that are able to repeatedly survive earthquakes.

economic, rational safety level, but for a higher safety level. In this way, the level that satisfies health risk and the gross cost minimization efficiency is called in the economic field the "Pareto" efficiency, and it exists as the solution to an equilibrium efficiency.

#67 International Cooperation in the Earthquake Disaster-Prevention Field

After World War II, Japan, which had become one of the world's poorest countries, was reconstructed after receiving support from World Bank and overseas NGOs. The money borrowed from World Bank was repaid in 1990, not that long ago. We must not forget that the foundation of Japan's current prosperity comes in part from the support we received from foreign countries.

There is no exception when it comes to earthquake disasters. After the 1923 Kanto earthquake, Japan received donations and support materials from over 50 various countries. Especially after the 1995 Kobe earthquake and 2011 Tohoku earthquake, Japan received warm support from many different countries.

Also, Japan's Official Development Assistance (ODA) was started right after the war, in 1954. In the 1990s Japan contributed over 1 trillion yen, making it the world's largest ODA contributor, but due to financial difficulties the budget is reduced each year. The background behind Japan's strength being put into ODA was partly as post-war reparations to other Asian countries, partly because highly trade-dependent Japan would also benefit from the development of other Asian countries, and partly because instead of military force, Japan would be making peace contributions.

ODA is largely separated into technological cooperation and aid (paid or free of charge). In the earthquake disaster field, large projects have been implemented with technological

3

プレートの衝突と地震の発生

地震は岩盤の破壊現象

ヴェーゲナーは、地球には初めに1つの大陸しかなく、分裂・移動して現在の各大陸になったのだと考えました。彼は、最初の大陸をギリシャ語で「すべての陸地」という意味でパンゲアと名づけました。プレートテクトニクスによれば、パンゲアが分裂した場所が現在の中央海嶺に当たります。分裂した大陸は数億年をかけて1つにまとまり、また分裂するというサイクルを繰り返すと考えられています。

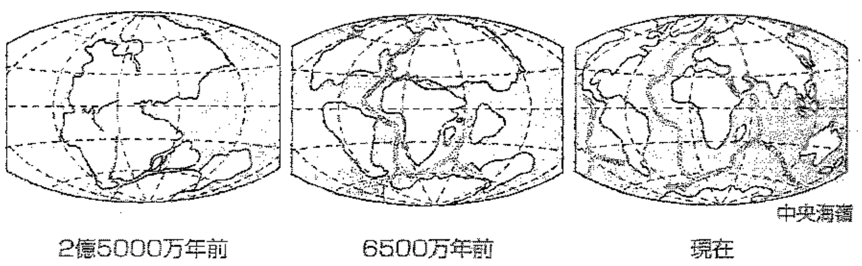
太平洋の東側の南米沖には、南北に走る中央海嶺があり、そこで生まれた太平洋プレートは年間8cmほどの速度で北西に移動してユーラシアプレートの下に潜り込んでいます。これは、大陸プレートと海洋プレートが衝突する典型的な例です。一方、大陸プレートと大陸プレートが衝突する場合もあります。かつてインドは独立の大陸でしたが、ユーラシアプレートに衝突して下に潜り込みながら陸地を押し上げた結果、海底が折り曲げられて8000mの高さに持ち上がりました。これがヒマラヤ山脈です。実際にエベレストの頂上では深海に棲むウミユリの化石が見つかっています。日本では、フィリピン海プレートに乗った大陸のかけらが日本列島と衝突してできたのが現在の伊豆半島です。その衝突によって、丹沢山地が形成されたといわれています。

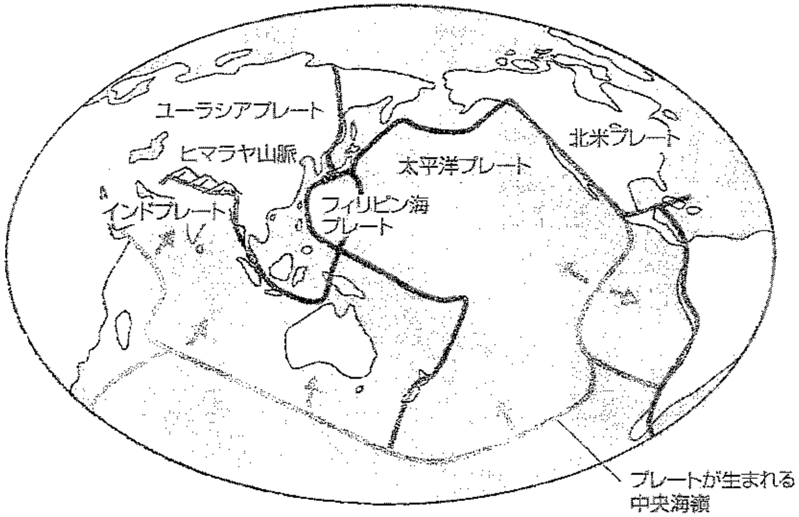
プレートがぶつかり合う境界やプレートの内部に歪が蓄積されると、ついには岩盤が破壊されて衝撃波が発生します。この現象を地震といい、衝撃波を地震波といいます。破壊される面を断層といいますが、いったん断層ができると、歪がたまるたびに同じ場所で破壊が起こりやすくなります。日本に地震が多いのは、日本列島が4枚のプレートがぶつかり合う世界でも類のない場所に位置しているからです。海洋プレートが沈み込む海溝のうち、とくに深さが6000mより浅いものをトラフと呼びますが、日本列島の東には日本海溝があり、南には南海トラフがあります。

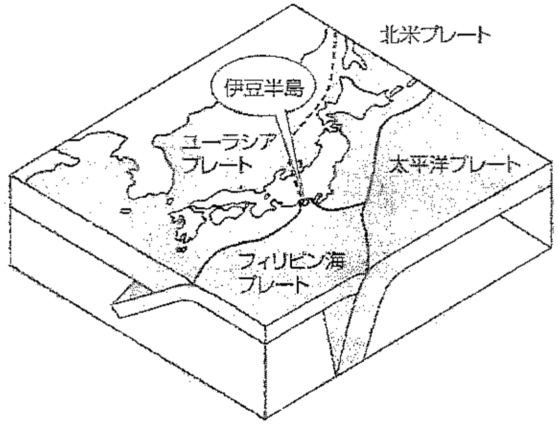
要点BOX

- ●大陸は分裂、移動、衝突を繰り返してきた
- ●岩盤の破壊による衝撃波が地震波、破壊面が断層
- ●日本は4枚のプレートがぶつかる地震多発国

プレートの誕生







6

地震のマグニチュードと震度

地震の規模と揺れの強さ

地震が起きたときに、テレビの画面に速報がテロップで流れるのを見たことがあると思います。速報では、震源の位置、地震のマグニチュード、各地の震度などが表示されます。マグニチュードは震源における地震のエネルギーを表し、震度は地面の揺れの激しさを表します。マグニチュードは地震ごとに1つだけ決まる値ですが、震度は場所によって異なり、一般に震源から離れるほど値は小さくなります。ちょうど、スピーカーの出力の大きさが一定でも、聞こえる音の大きさは場所が離れると小さくなるのと同じ原理です。

マグニチュードの値は地震計の記録から計算しますが、国際的に統一された規格はありません。日本では気象庁が発表する気象庁マグニチュードM_Jが標準とされています。外国では地震のエネルギーに基づくモーメント・マグニチュードM_wを用いることが多いようです。1995年兵庫県南部地震のマグニチュードは、M_Jでは7・3、M_wでは6・9です。定義によって値が異なるので、比較のときには注意が必要です。モーメント・マグニチュードの方が大きな地震の規模を表すのに適しているので、2011年東北地方太平洋沖地震（東北大震災）ではモーメント・マグニチュードM_wの9・0が使われています。

地震のエネルギーの大きさは「断層の面積」に「すべり量」を掛けた値に比例します。マグニチュードが1つ増えると地震のエネルギーは約30倍になりますが、これは断層の長さが約3倍（面積が10倍、すべり量が3倍）になることに相当します。マグニチュード5の地震の断層長さは約4㎞ですから、この比率を使うと、マグニチュード6で12㎞、マグニチュード7で40㎞、マグニチュード8で120㎞と増えていきます。マグニチュード9・0の東北地方太平洋沖地震は、断層の長さが約500㎞でした。これまでに観測された最大の地震は、1960年に発生したチリ地震で、マグニチュード9・5、断層の長さが約800㎞です。

要点BOX
- ●マグニチュードは地震のエネルギー
- ●震度は地面の揺れの激しさ
- ●マグニチュードが1つ違うとエネルギーは30倍

マグニチュードの求め方

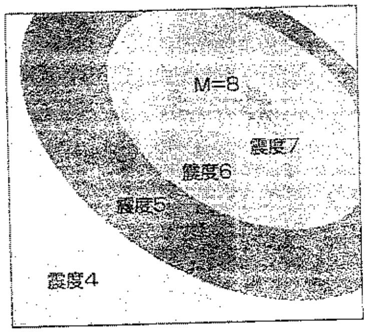
モーメント・マグニチュードMwを求める式

$$M_W = (\log M_0 - 9.1)/1.5$$

$$M_0 = \mu \times D \times S$$

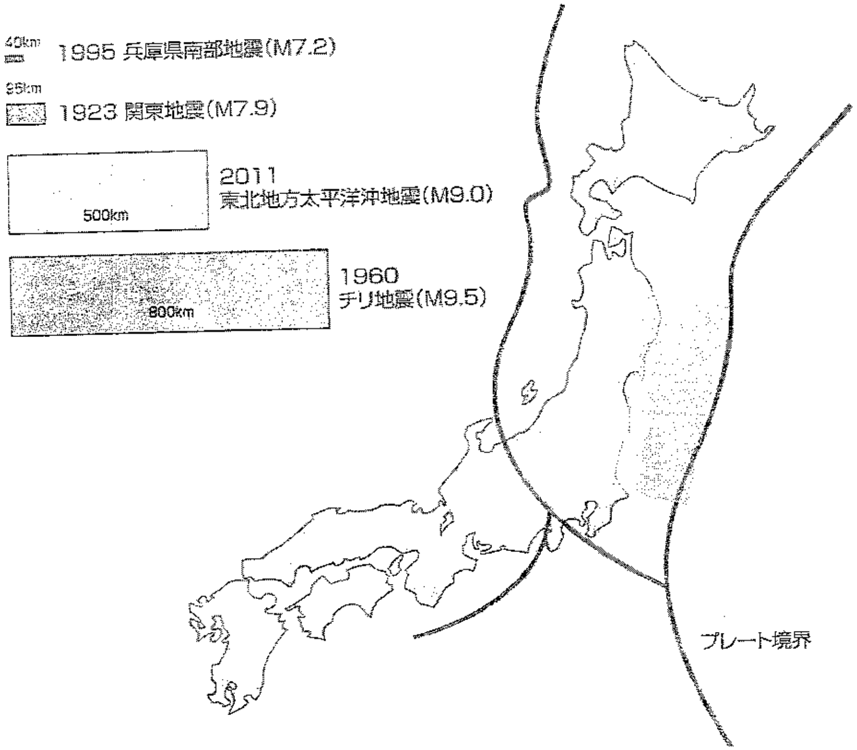
M_0：地震モーメント (Nm)
μ：剛性率($\mathrm{Pa} = \mathrm{N/m^2}$)
D：断層の平均すべり量(m)
S：断層の面積($\mathrm{m^2}$)

たとえば $\mu = 40\mathrm{GPa}$, $D = 10\mathrm{m}$、
$S = 500\mathrm{km} \times 200\mathrm{km}$
とすると、$M_w = 9.0$ となる。



マグニチュードは1つだけ決まる。震度は震源から離れるほど小さくなる

断層の長さ



8

全国に張り巡らされた強震観測網

地震計で地面の揺れを計測することで、地盤の堅さから地球内部の構造までさまざまなことがわかります。一口に地震計といっても、さまざまな種類があります。広帯域地震計は、大地震に伴う周期100秒といったゆっくりとした地面の揺れを捉えることができる地震計です。地球内部の構造や震源メカニズムの解析に用いられますが、強い揺れの計測には適していません。一方、強震計は、比較的短周期の強い揺れを計測できる地震計です。これに震度計算の機能を組み込んだものが震度計です。強震計の記録は、断層の破壊過程の解明、地震被害の分析、構造物の耐震設計などに幅広く利用されています。

全国的な強震観測網として代表的なものに防災科学技術研究所のK-NETやKik-netがあります。K-NETは全国に約1000カ所、Kik-netは約700カ所の観測点があり、全国を均一にカバーしています。これほどの観測網が整備されたのは、兵庫県南部地震(1995年)のあとです。それまでは、国土交通省港湾局の港湾地域強震観測や建築研究所による建物の強震観測など、限られた機関がそれぞれの目的に応じた観測を行っていました。

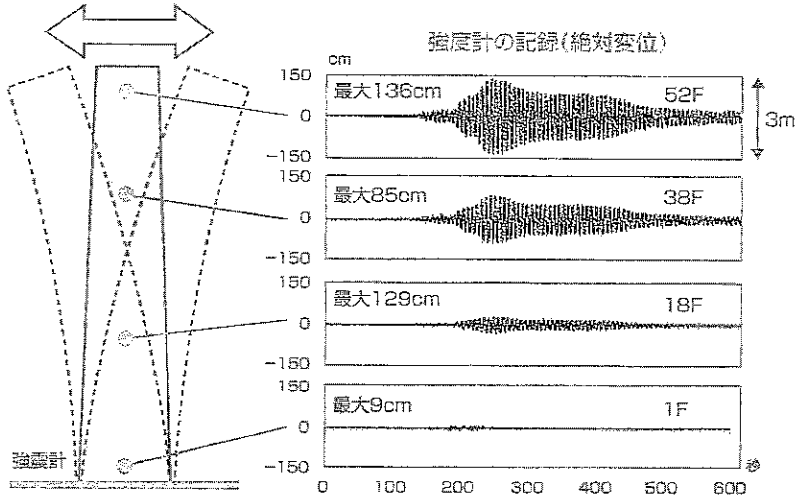
建物に強震計を付けることで、地震に対する建物の耐震性能を知ることができます。免震や制振などの新しい技術も、建物の揺れを観測して、その効果が確認されて普及が進みました。東北地方太平洋沖地震では、震源から遠く離れた大阪の超高層で、往復3m近い揺れが起きたことが強震計の記録から明らかになりました。大阪の堆積盆地で発生した長周期地震動が原因と考えられています。

残念ながら、地表に比べて建物の観測点や観測記録ははるかに不足しています。地震直後に観測記録から建物の健全性を判断して避難指示に役立てる取り組みも始まっており、今後、建物の強震観測が普及することが期待されます。

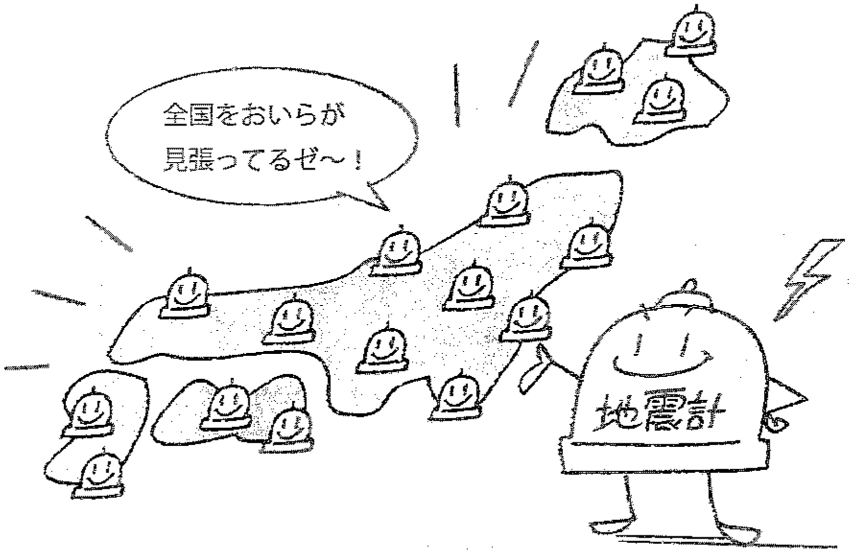
要点BOX

- ●強震計の記録は耐震設計などに利用されている
- ●全国をカバーするK-NET強震観測網
- ●強震観測からわかる建物の健全性

東北地方太平洋沖地震での大阪の超高層の揺れ



出典：建築研究所の強震観測データ



全国をカバーする強震観測網(K-NET, Kik-net)

13 加速度と慣性力

頑丈な建物が地震で倒れる理由

地震で激しく地面が揺れると、立っていることが難しくバランスを崩して転ぶことがありますが、大ケガになることはめったにありません。一方、人間よりもずっと頑丈に作られているはずの建物が、地震の揺れで倒壊することがあります。なぜ人は平気なのに頑丈な建物は壊れてしまうのでしょうか。

人に作用する力として、最も身近なものは地球の引力です。みなさんの体重は、身体に働く地球の引力の大きさを表しています。もし地球よりも引力の小さい月の上で体重を計ったら、体重計の数値はずっと小さな値になります。このことを理解するために、体重を「質量」と「重力加速度」の積で表します。質量は物に固有の値ですが、重力加速度は地球と月では異なります。月の重力加速度は地球の約1／6なので、体重も約1／6になります。

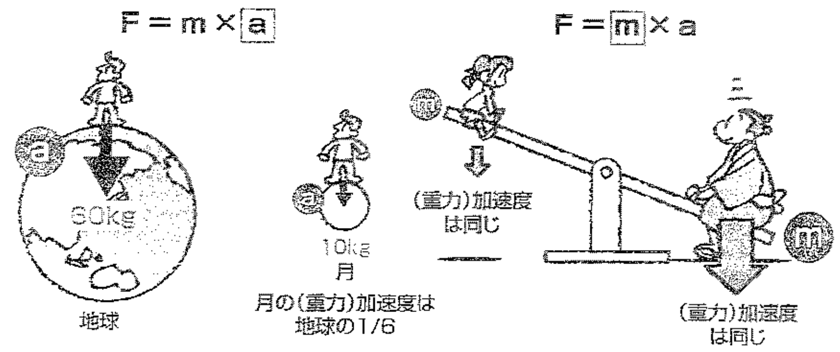
加速度は下向きにだけ働くとは限りません。バスに乗っているときに、バスが急発進すると身体が後ろに倒れそうになります。また、バスが急停止すると、今度は身体が前に倒れそうになります。乗っている人に加速する（あるいは減速する）方向と逆の力が働きますが、この力を慣性力といい、体重と同じように物体の質量と加速度の積で表されます。すなわち、加速度が大きいほど、また質量が大きいほど、働く慣性力は大きくなります。バスが急停止すると、太った人の方がやせた人よりも大きな慣性力がかかるので、自分の体を支えることが難しくなります。

地震で地面が揺れると、人よりも建物の方がずっと質量が大きいので、建物にはそれだけ大きな慣性力が働きます。つまり、地震の揺れで人が平気なのに建物の方が壊れてしまうのは、建物が慣性力を支えきれなくなるためです。一般に建物は重力を支えるために上下に強い構造ですが、地震による左右の慣性力には弱い構造です。とくに煉瓦や石を積み上げた組積造建物は地震の際に脆く崩れることがあります。

- ●体重は質量と重力加速度の積
- ●慣性力は質量と水平加速度の積
- ●一般に建物は上下に強く、左右に弱い構造

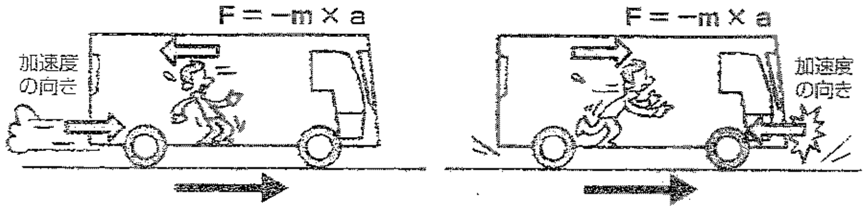
鉛直と水平の力

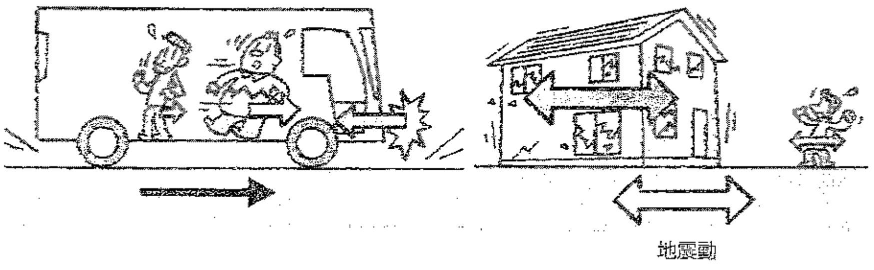
鉛直に働く力：体重(F) ＝ 質量(m) × 重量加速度(g)



水平に働く力：慣性力(F) ＝ 質量(m) × 水平加速度(a)

加速度と逆方向の力(慣性力)が働く　　加速度と逆方向の力(慣性力)が働く





15

定規を使った実験①

免震構造の基本原理

地震による地面の揺れに建物が共振すると、大きな揺れが発生します。地面の揺れの周期と建物の揺れの関係を表したグラフを共振曲線といいます。簡単な実験を通して、共振曲線を描いてみましょう。

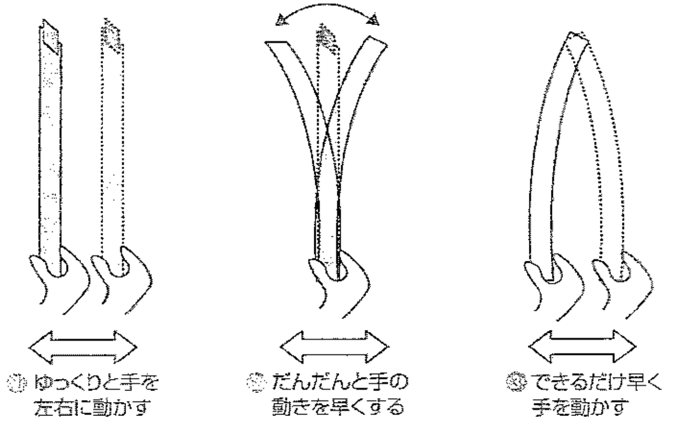
用意するのは、30㎝ほどのプラスチックの定規と大きめのクリップです。クリップを定規の先に付けて錘の代わりにします。クリップと反対側の定規の端をしっかり握って、定規を立ててください。①最初に、定規を持った手を、左右にできるだけゆっくりと動かしてみます。定規はまったく変形せずに、そのまま平行に移動します。②次に、手の動きを少し早くしてみます。だんだんと、定規がしなるように変形をして揺れ始めたでしょうか。とくに、ある特定の早さで手を左右に動かしたときに、定規が大きく揺れることを確かめてください。この周期が定規の固有周期です。③さらに、できるだけ早く手を左右に動かしてみましょう。こんどは手元だけが動いて、定規の先があまり動かないようになるはずです。揺れの周期と定規の振幅の関係を描いたのが共振曲線です。

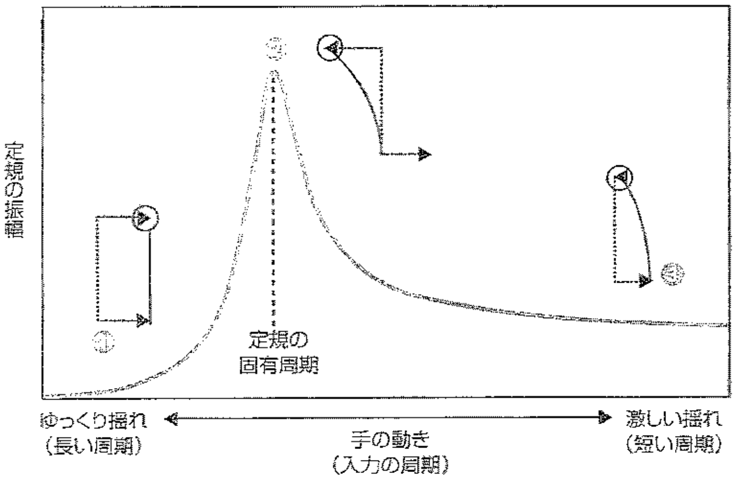
ここで、注目したいのが③の状態です。手を激しく左右に動かしているのに、定規の先は動いていません。これは定規の固有周期が入力の周期よりも十分に長い場合に起きる現象です。これを建物に応用すれば、地震で地面が激しく揺れても、建物の上はじっと動かないようにできるかもしれません。ただし、そのためには、地震動が持つ主要な周期よりも建物の固有周期を十分に長くしておく必要があります。

免震構造の建物では、建物と地面との間に、ゴムなどで作られた免震装置が設置されています。この免震装置の水平剛性がとても小さい（柔らかい）ので、建物の固有周期を2～4秒と長くすることができます。免震構造では、地面の激しい揺れが建物に伝わらないので、建物本体だけでなく室内の家具や設備などを地震から守ることができます。

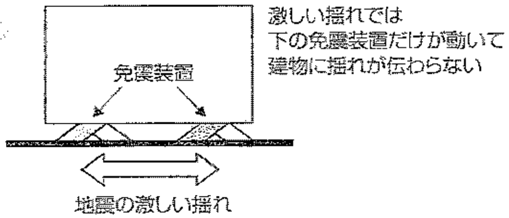
- ●地震の揺れの周期と建物の揺れの関係は共振曲線でよくわかる
- ●建物を長周期化する免震構造

定規で確かめる共振現象





免震装置を付けて
建物の固有周期を
長くする



19

地震動の応答スペクトル

剛な建物と柔な建物

建物に被害を及ぼすような強い地震動を記録するには、強震計と呼ばれる特別な地震計が必要です。1931年に米国に招かれた末広恭二博士が強震計を使った観測を提唱したことから、日本に先駆けて米国で実用化されました。

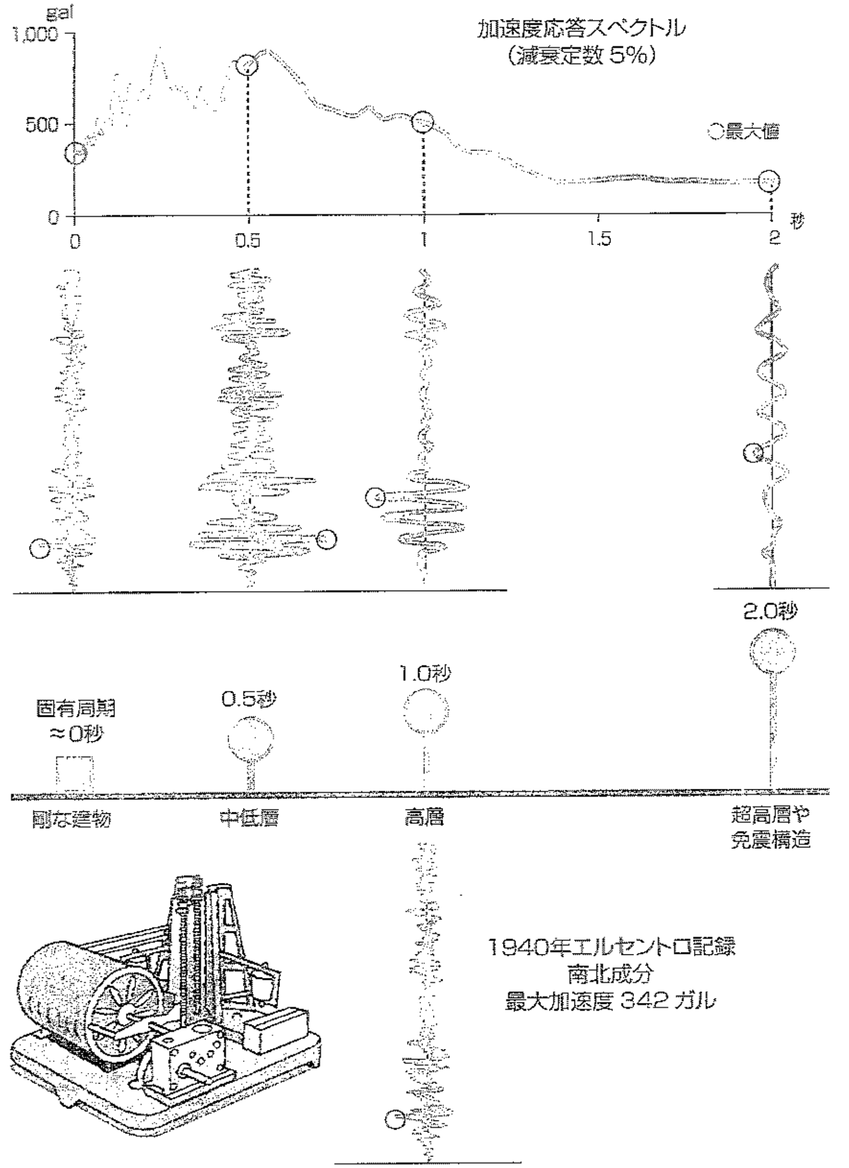
最初の強震記録は、米国・カリフォルニア州インペリアル・バレイの地震（1940年、M7・1）におけるエルセントロ変電所の記録です。現在でも耐震設計の標準的な地震動として使われています。この記録の南北成分の加速度記録から振動方程式を用いて建物の揺れを求めてみましょう。

固有周期ごとに建物の揺れの最大加速度をプロットしたグラフを加速度応答スペクトルといいます。グラフから、①スペクトルの山はおおむね固有周期1秒以下にあり、固有周期の短い中低層の建物が大きく揺れること、②逆に固有周期が1秒を超えるような高層建物や免震建物の揺れは小さくなることがわかります。また、③共振する周期0・5秒付近では、建物の応答加速度は地面の加速度の2～3倍に達することがわかります。一方、④建物の固有周期がゼロの近辺では倍率は1になります。これは、建物ががっしりと強固（剛）に造られており、地面と一緒に動くことを意味します。

戦前戦後にかけて、研究者の間で地震に対して建物を剛に造るべきか柔らかく造るべきかで大論争になりました。これを"柔剛論争"といいます。確かに建物が剛であれば応答倍率は1ですみますが、建物を柔らかくして固有周期を長くすれば応答倍率を1よりも小さくできます。当時は地震動の性質がまだよくわからず、建物も低層のものが多かったこともあり、地震に対しては建物を壁や筋交い（すじか）で固めて剛構造とする考えが主流を占めました。柔構造の実現には超高層や免震構造のような高度な建設技術が必要だったのです。

●米国で始まった強震観測
●応答スペクトルから建物の揺れの大きさがわかる
●建物の造りで柔剛論争が起きる

地震動と応答スペクトル



用語解説

筋交い：柱と柱の間に斜めに入れる部材。

21

地盤による揺れの違い

断層の破壊により発生した地震波は、地殻の上面である地震基盤までは一様に伝播すると考えられます。地震波は柔らかい堆積層を通過すると、屈折の法則（スネルの法則）により波の進行方向が徐々に上向きになり、波の速度が遅くなる分、振幅が増大します。

地震基盤は、新第三紀（2400万年～170万年前）に形成された固い岩石です。地震基盤より上の堆積層のうち、第四紀更新世（170万年～1万年前）の地層は、超高層建物を支えるだけの剛性と強度を持っていることから工学的基盤と呼ばれます。さらに上には、締め固まっていない土が堆積した表層地盤があります。表層地盤は、河川による堆積作用によって形成された沖積層と埋立てによる層からなり、かつて湾や海であった場所に厚く堆積しています。

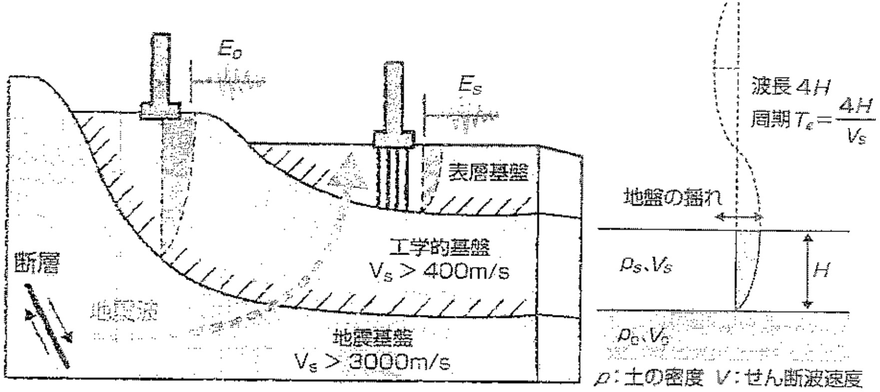
たとえば、東京の湾岸地域の表層地盤の厚さは50m以上あり、超高層建物を支えるために、多くの杭を地中深く工学的基盤まで打つ必要があります。

一方、初期の超高層建物は、西新宿など表層地盤の浅い地域に多く建設されており、深さ10～15mほどの工学的基盤の上に基礎が置かれています。杭のない直接基礎ですが、十分な大きさと根入れ深さを確保しているので、地震で建物が転倒する心配はありません。

地盤も建物と同じように揺れやすい固有周期があり、1次の固有周期Tは、地盤の厚さHを1／4波長とした$T=4H/V$（ここにVは地盤の平均せん断波速度）で計算することができます。工学的基盤が露頭している場所の揺れE_0と表層地盤上の揺れE_sを比較すると、1次の固有周期での揺れの増幅は2～5倍にもなります。増幅率は、地層のインピーダンス比（密度×せん断波速度の比）の逆数に比例します。つまり、柔らかい地層ほど地震波は増幅されて揺れが大きくなります。地震による住宅の被害が軟弱地盤に集中するのはそのためです。

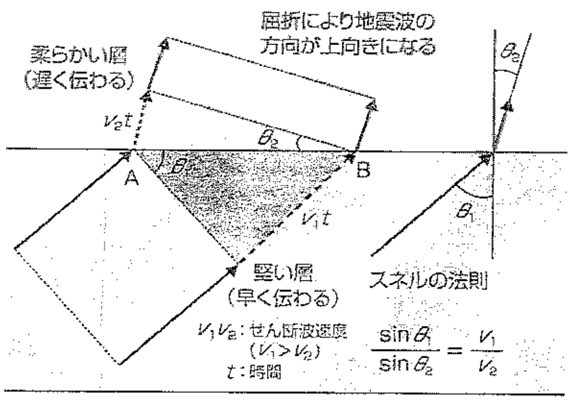
- ●地震波は、地震基盤、工学的基盤、表層地盤と伝わり建物に到達する
- ●地盤が軟弱なほど揺れの増幅が大きい

地盤で増幅される地震波



地盤増幅率 $E_s/E_0 \propto 1/\alpha_s$ ここに、$\alpha_s=\frac{\rho_s V_s}{\rho_0 V_0}$：インピーダンス比

地震波が真下から来る理由



2つの媒質の間を波が入射して進路が曲がることを屈折という。
入射角度θ_1と屈折角度θ_2および2つの媒質の波の速度v_1、v_2の関係を表した式をスネルの法則という。

地盤の特性

	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
軟弱地盤			＜100	1.5～2	20
表層地盤	土 （沖積層）	第四紀（完新世） 1万年前～現代	＜400	2	5～20
工学的基盤	軟岩 （洪積層）	第四紀（更新世） 170万年～1万年前	＞400	2～3	5～20
地震基盤	岩石	新第三紀 2400万年～170万年前	＞3000	3	1～5

第　章

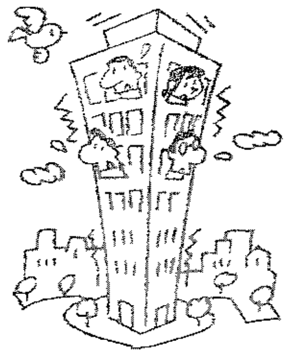
Column

大変熱心な自治会の協力をいただいて、東京のある超高層マンションで出前講義をしました。事前に構造計算書を見せていただいたので、マンションの耐震性について一通り説明をしたあと、近くで観測された2011年の東日本大震災の記録をもとに建物の揺れを再現してみました。揺れの大きさは建物の安全性にはまったく影響がない程度のものでしたが、住民の方の体感ではもっと大きな揺れに思えたそうです。

さらに、将来起きると考えられる首都直下型地震による揺れの予測もしました。みな自分の住む階がどうなるのか興味津々です。建物にひび割れが発生するものの、倒壊するような被害は起きないという結果になりました。もちろん、計算結果は一つの例にすぎないこと、本当の地震では違う結果になることを説明しています。講義のあと、高層階に住む高齢の女性からは、東日本大震災のあと恐怖でめまいに悩まされて病院通いをしていたが、この講義を聞いて安心したとの感謝の言葉をいただきました。ほかにも、非常に役に立った、水・食糧の備蓄をしなければと実感した、など好意的な意見を多くいただきました。一方、地震被害でマンションの資産価値が下がることを心配する声もありました。

この出前講義は、専門家が住民の自助努力を支援する方法を考える試みとして行ったものです。なにより、マンションが地震で揺れるアニメーションを見せたとたんに、他人事だった防災がわが身のことに意識が変わるのがわかりました。

現在、内閣府において、マグニチュード9クラスの南海トラフ巨大地震の検討が進められています。国の浮沈に関わる問題ですが、想定される揺れはあまりにも大きく、予想される被害も甚大です。この場合は、建物の揺れの再現はかえって住民の恐怖を煽ることになるかもしれません。国の防災対策のために想定する地震と、建物の設計で想定すべき地震とでは、自ずとレベルが異なるはずですが、そうした議論はまだ十分にはなされていないようです。



24

関東大震災の衝撃と教訓

煉瓦造から鉄筋コンクリート造へ

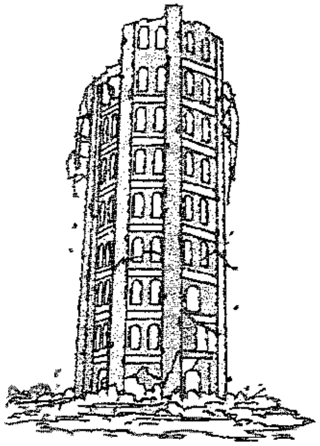
1923年9月1日の正午2分前に、マグニチュード7・8の関東大震災が起きました。10万棟を超える家屋が倒壊し、炊事の火が燃え移った火災は強風にあおられて大火となり、家屋の倒壊による圧死者に加えて大量の焼死者が出ました。死者・行方不明者は約10万5000人にのぼり、そのうち約9万人は火災により亡くなったといわれています。とくに、陸軍被服廠跡の公園に避難した約4万人のほとんどが炎の竜巻（火災旋風）に巻き込まれて焼死しました。

関東大震災により、煉瓦造建物は甚大な被害を受けました。銀座煉瓦街は壊滅し、浅草のランドマークであった12階建ての浅草凌雲閣は崩れ落ちました。鉄骨で補強した新しい煉瓦造建築物も一部を除いて被害を免れることはできず、煉瓦造はその後、建築物の主体構造として使われることはほとんどなくなりました。一方、耐震性、耐火性ともに優れた鉄筋コンクリート造は、日本の市街地建築物の主役に躍り出ました。

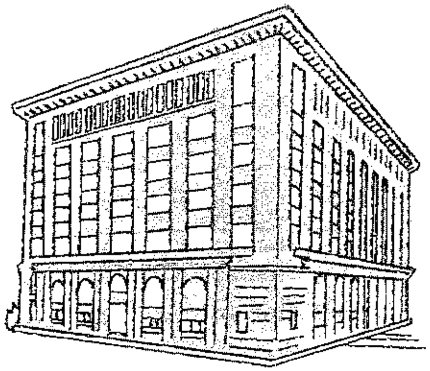
関東大震災を契機に普及した日本発祥の構造技術があります。当時、米国流の鉄筋コンクリート造や鉄骨造建築物は、帳壁（耐力を負担しない壁）に煉瓦を用いることが一般的で、鉄骨の耐火被覆にも煉瓦が使われていました。そんな中、内藤多仲博士は、建物がどんな地震にも耐えるように、帳壁の煉瓦を鉄筋コンクリートに置き換えた耐震壁や鉄骨の耐火被覆に鉄筋コンクリートを用いた鉄骨鉄筋コンクリートを考案し、東京丸の内にあった日本興業銀行本店に採用しました。竣工からわずか3カ月後に関東大震災が起きましたが、建物はほとんど被害を受けませんでした。この耐震壁のアイデアは、内藤博士が米国に留学中に使っていたトランクの仕切りから思いついたということです。ちなみに、内藤博士は、東京タワーや大阪の通天閣など、多くの鉄塔を手がけた塔博士としても知られています。

●関東大震災によって煉瓦造建物は壊滅的な被害
●耐震壁や鉄骨鉄筋コンクリートは日本独自の技術

関東大震災時の建物



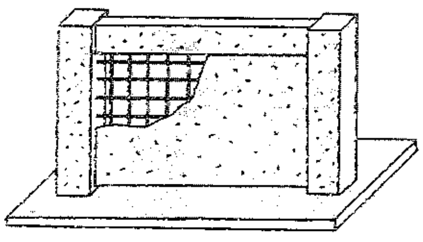
崩壊した浅草凌雲閣



ほぼ無傷で耐えた
旧日本興業銀行本店

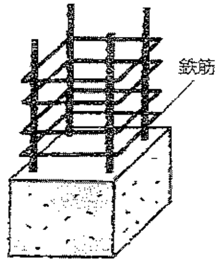
赤煉瓦造で12階建て、52mの浅草凌雲閣も崩壊

内藤多仲博士が考案した日本独自の構造

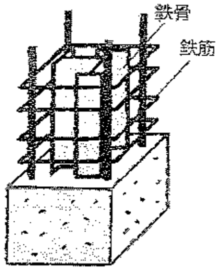


鉄筋コンクリート造耐震壁

内藤多仲博士
（1886～1970）



鉄筋コンクリート造柱



鉄骨鉄筋コンクリート造柱

26

耐震設計法の流れ

どのように設計されているのか

実は、ほとんどの戸建住宅では構造計算が義務付けられていません。こうした建物は建築基準法第6条第1項第4号に規定されていることから4号建築物と呼ばれます。もともと在来木造住宅は大工による伝統的な技能で建築されて、経験的に安全性が確かめられています。ただし、基礎を鉄筋コンクリート造にすることや筋交いや合板の壁を十分に入れること（壁量規定）などの構造規定が定められています。

高さ60mを超える超高層建物では、地震による時々刻々の建物の揺れを計算する時刻歴解析が義務付けられています。それ以外の建物は静的な地震力を用いた一次設計に進みます。建物が低層で壁が多ければ、一次設計のみの「ルート1」になります。これは剛構造に対する水平震度0・2の震度法の考え方にほかなりません。それ以外は二次設計に進みます。

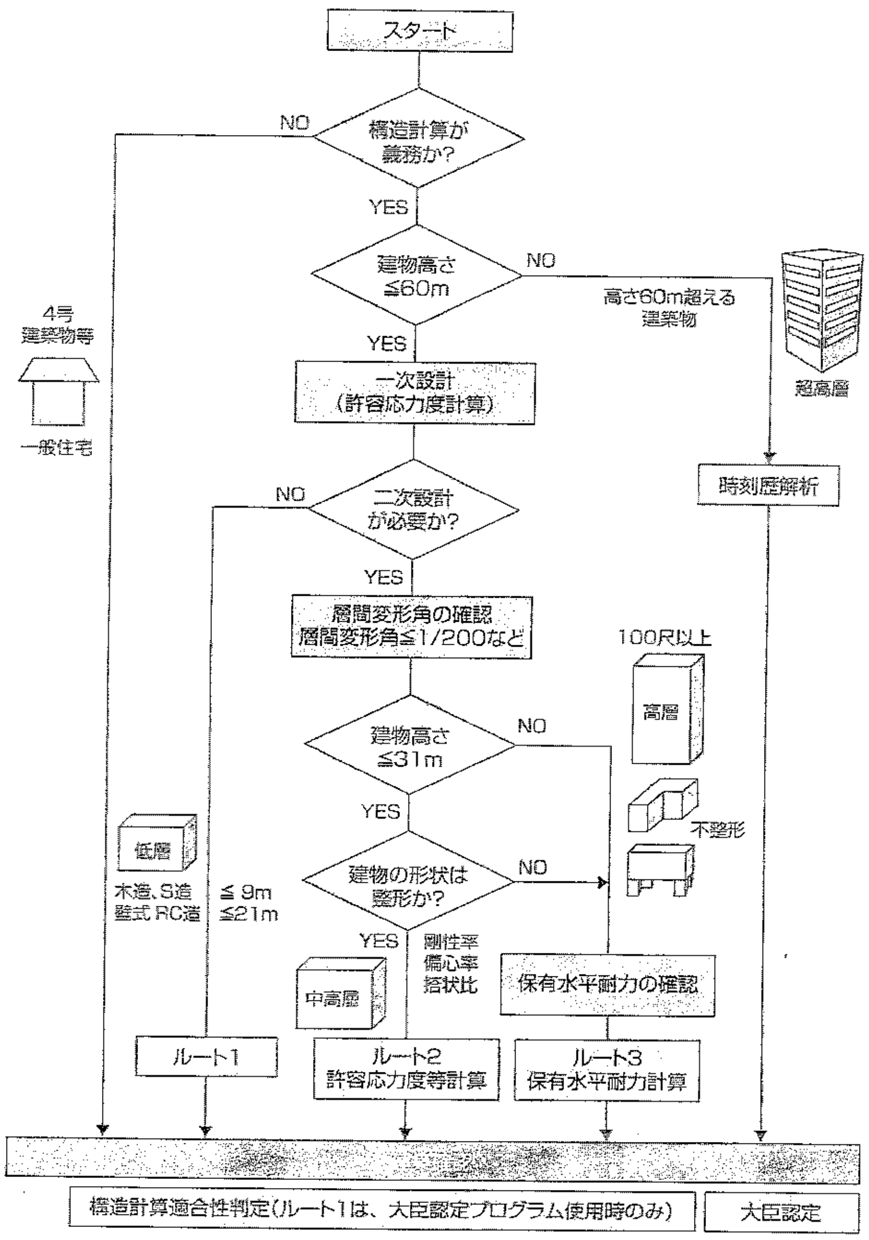
二次設計では、外壁や窓ガラスなどの非構造部材が損傷しないように、一次設計の地震力（水平震度0・2相当）に対する建物の層間変形角が制限されます。次に、建物の高さが31mを超えるかどうかでルートが分かれます。高さ100尺制限の名残です。高さ31m以下で形状が整形であれば、建物をできるだけ剛にする「ルート2」に進みます。それ以外は、水平震度1・0相当の地震力に対して倒壊しないことを確かめる「ルート3」（保有水平耐力計算）に進みます。

設計図書は、地方自治体の「建築主事」または民間の「指定確認検査機関」の審査（建築確認）を受けなければなりません。この際、計算ルートにより、構造計算の正しさを確認する構造計算適合性判定や専門家の委員会による大臣認定が求められます。

このように、耐震設計には、建築士におまかせの4号建築物から、剛構造の「ルート1」、強度で抵抗する「ルート2」、大地震では壊れても靱性（粘り）に期待する「ルート3」など、さまざまなメニューがあるのです。

要点BOX
- ●建物によって構造計算ルートが異なる
- ●耐震設計法には歴史と経験が反映されている

構造計算のフロー



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急がれる耐震改修

危ない建物はまだたくさんある

建物の耐震性は、１９８１年の建築基準法施行令の改正を境に大きく向上しました。そのため、この基準を新耐震基準と呼ぶことがあります。阪神淡路大震災では、新耐震基準で設計された建物の被害は限定的でした。そのため、新耐震基準の耐震性はおおむね妥当と考えられています。一方、基準の改正前に設計された建物に被害が集中しました。そうした建物は、既存不適格建物として、耐震性が低くても放置されていたのです。

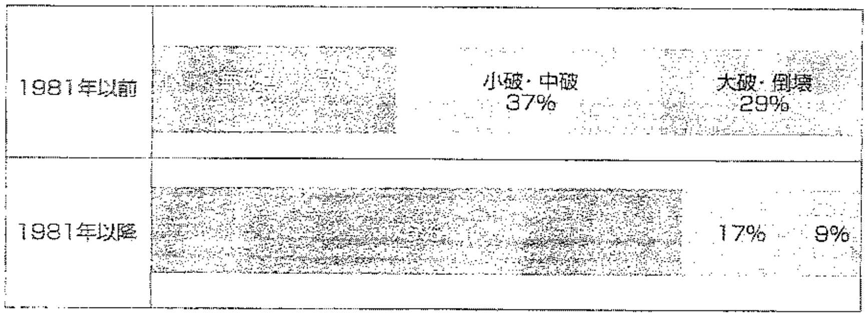
阪神淡路大震災の被害を受けて、１９９５年12月に既存不適格建築物の耐震改修・補強を目的とした「建築物の耐震改修の促進に関する法律（耐震改修促進法）」が施行されました。耐震改修促進法は、学校、老人ホーム、病院、百貨店など多くの人が利用する規模の大きな建物のほか、危険物を取り扱う建築物や地震で倒壊した場合に避難路や緊急輸送道路をふさぐ可能性のある建築物について、現行の耐震基準を満足しないものを対象としています。これらをまとめて特定建築物といいます。この法律により、特定建築物の耐震診断や改修に対して、補助金や交付金、低金利の融資制度、ローン減税などの優遇措置を受けることができます。また、地方自治体には、耐震改修促進計画の策定と特定建築物の所有者に対する指導が義務付けられました。

公立小中学校に対しては、１９９５年６月に地震防災対策特別措置法が施行され、耐震補強や改築に対する国庫補助率が定められました。補助率は、２００８年の中国四川大地震で多くの学校が倒壊したことをきっかけに引き上げられ、耐震補強では２／３、改築では１／２の費用を国が補助することになりました。

戸建住宅は、道路閉塞の危険があるものを除き、こうした法律の対象ではありませんが、多くの自治体が耐震診断や改修に対する補助を実施しています。

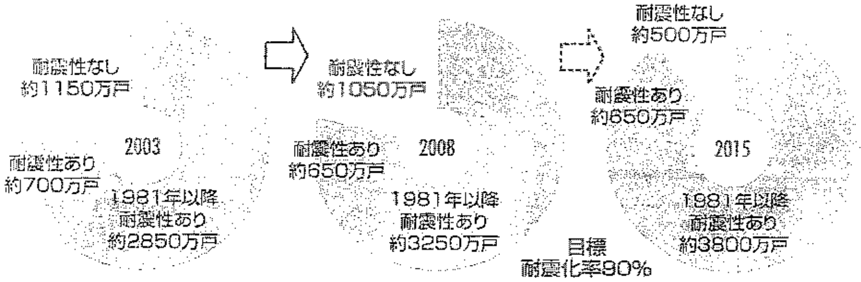
●特定建築物を対象とした耐震改修促進法
●公立小中学校が対象の地震防災対策特別措置法

阪神淡路大震災による年代別の建物被害



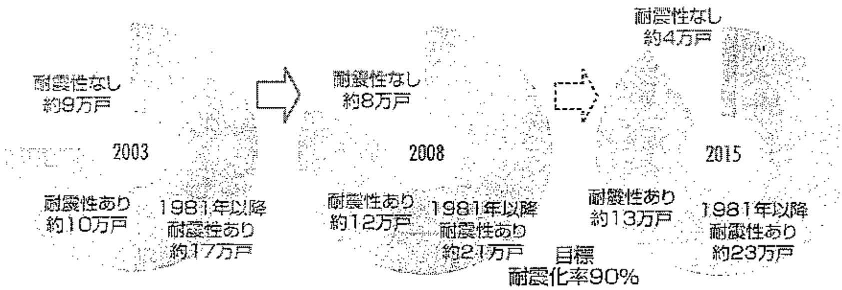
出典：「平成7年阪神・淡路大震災調査委員会中間報告」建設省より作成

[illegible]の耐震化の進捗状況



出典：国土交通省ホームページより作成

[illegible]の耐震化の進捗状況



出典　：国土交通省ホームページより作成

30 建物の用途や重要度による耐震性の違い

重要度係数が高い建物

一般の建物は建物重量のおよそ0・3倍の水平力で壊れ始め、その安全目標は歴史的に変わっていないことを解説しました。厳密には、地震の多い場所かどうか（地震地域係数Z）、地盤が軟弱かどうか（振動特性係数Rt）、構造に靭性や減衰性があるかどうか（構造特性係数Ds）、建物の形状や重心に偏りがないかどうか（形状特性係数Fes）を加味し構造計算をするので、壊れ始める水平力（設計用地震力）には建物ごとに違いがあります。

しかし、建物の用途や重要度の違い（用途係数または重要度係数）は地震力の計算では考慮されていません。つまり、マンションでもオフィスビルでも同じ地震力で設計されます。これは、建築基準法が公共の福祉のための最低限の基準であり、用途によって安全性に差を付けないためだと考えられます。ところが、法的に重要度係数が位置付けられている建物があります。官庁施設と発電用原子炉施設です。

官庁施設の多くは、地震災害時には防災拠点として機能することが求められます。そのため、Ⅰ類施設（内閣府、消防庁など）では1・5、Ⅱ類施設（地方気象台、港湾事務所など）では1・25、Ⅲ類施設（Ⅰ、Ⅱ以外の官公庁施設）では1・0の重要度係数を掛けた地震力を用います。

なお、東京都や静岡県のように、独自の指針を設けて学校、病院、図書館など公共性の高い建物を対象に重要度係数を導入している自治体もあります。とくに静岡県では、東海地震が切迫していることから、重要度係数に加えてすべての建物を対象に地震地域係数を1・2にしています。

世界のほとんどの国では最初から耐震規定に重要度係数が含まれています。また、中国の耐震規定では、北京や上海などの大都市の地震力を、都市機能の確保の観点から、ほかの地域よりも高く設定しています。

要点BOX

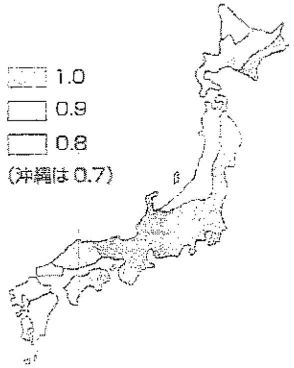
- ●日本の耐震規定には重要度係数がない
- ●法的に重要度係数があるのは官庁施設と発電用原子炉施設

1階の建物耐力と建物重量の比率を求める算定式

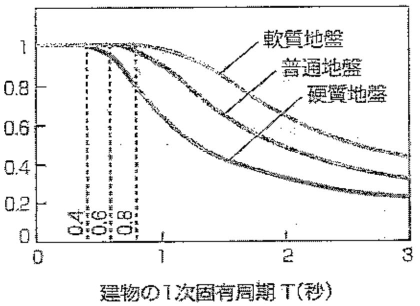
$$C_1=[Z][R_t][D_s][F_{es}][C_o]\quad (C_o=1.0)$$

①　②　③　④

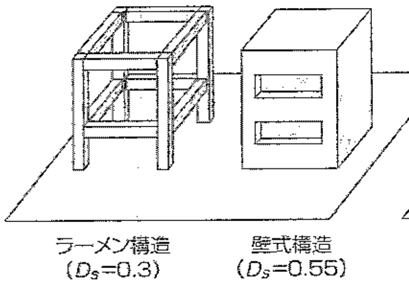
Z：地震地域係数(0.7〜1.0)



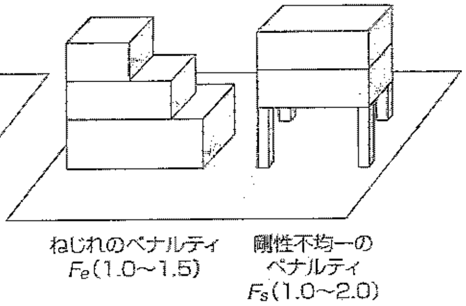
R_t：振動特性係数(<1.0)



D_s：構造特性係数(0.25〜0.55)



F_{es}：形状特性係数($F_{es}=F_e \times F_s$、1.0〜3.0)



例）　東京の普通地盤に建つ鉄筋コンクリート造建物（中低層、ラーメン構造、整形）
Z(東京)=1、R_t(普通地盤、中低層)=1、D_s=0.3(ラーメン構造)、F_{es}=1(整形)→C_1=0.3

重要度係数がある官庁施設

[illegible]	[illegible]
Ⅰ種(1.5)	災害対策施設(内閣府、消防庁、警察庁など) 災害拠点病院
Ⅱ種(1.25)	災害対策施設(地方気象台、港湾事務所、警察大学校など) 避難所として指定された学校
Ⅲ種(1.0)	その他の一般官公庁施設

出典：国土交通省「官庁施設の総合耐震計画基準」2006年

38

住宅の耐震性能を知る

住宅性能表示制度

みなさんが住宅を選ぶときには、どのような性能に基づいて決めるでしょうか。住宅の地震に対する安全性（耐震性）については、「たぶん安全だろう」という程度のあいまいな認識しかないのではないでしょうか。耐震性だけでなく、大雪や火災のときの安全性や劣化に対する耐久性など、住宅の構造に関わる性能（構造性能）は、イメージがつかみにくく、わかりにくい面があります。

2000年4月1日に「住宅の品質確保の促進等に関する法律」（住宅品確法）が施行されました。この法律により、さまざまな住宅の性能に関する共通のルールが提示され、公正な第三者機関による評価システムができあがりました（住宅性能表示制度）。

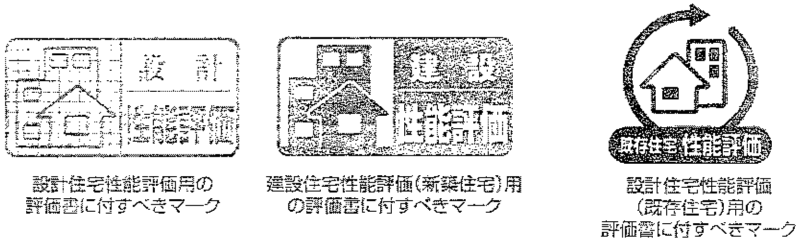
新築住宅については、設計図書などを「指定住宅性能評価機関」に提出し、評価を受けた後に設計住宅性能評価書が交付されます。これを契約書に添付すると、その性能がそのまま契約事項になります。

さらに、現場検査を行って性能が確認されると、建設住宅性能評価書が交付されます。既存住宅では、目視による現況調査と評価に基づき建設住宅性能評価書（現況検査・評価書）が交付されます。表示すべき性能の項目は10項目に上り、表示方法は「日本住宅性能表示基準（平成12年建設省告示1652号）」に、性能の評価方法は「評価方法基準（平成12年建設省告示1654号）」にそれぞれ規定されています。

たとえば、地震に対する性能は耐震等級と呼ばれ、建築基準法の地震力との比率で1から3の等級があります。免震構造は地震力にかかわらず最も高い等級3です。住宅性能表示制度を利用すれば、設計者に「私の住宅を耐震等級3にしてください」というような頼み方ができます。また、中古住宅を市場で売買するときにも、等級が高ければそれだけ買い手が多く見つかるかもしれません。さらに、耐震等級が高いと地震保険が割引になる利点もあります。

●住宅の耐震性能を表す耐震等級
●耐震等級が高いと地震保険も割引に

住宅性能表示制度の評価書に付けられるマーク



設計住宅性能評価用の評価書に付すべきマーク

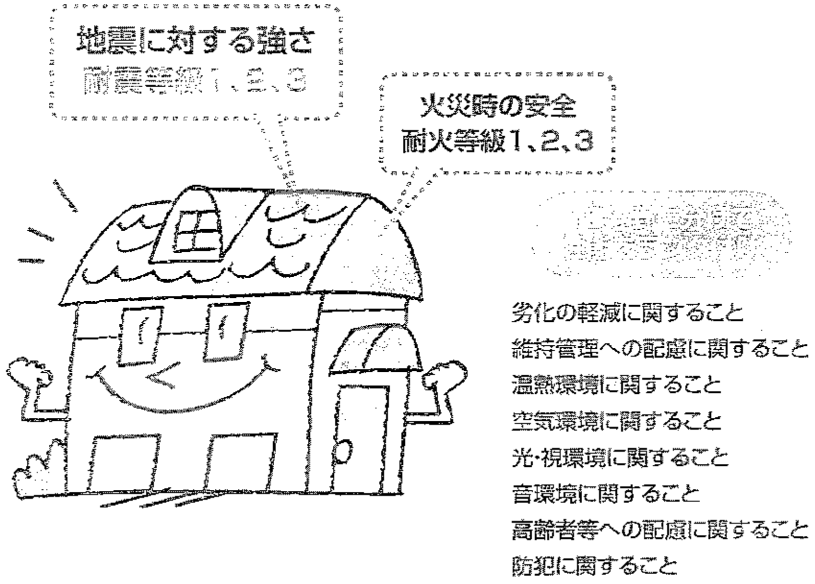
建設住宅性能評価（新築住宅）用の評価書に付すべきマーク

設計住宅性能評価（既存住宅）用の評価書に付すべきマーク

(a) 新築住宅に付けられるマーク　(b) 既存住宅に付けられるマーク

出典：国土交通省

住宅の性能表示項目



劣化の軽減に関すること
維持管理への配慮に関すること
温熱環境に関すること
空気環境に関すること
光・視環境に関すること
音環境に関すること
高齢者等への配慮に関すること
防犯に関すること

○耐震等級の違いは何を表すの？

耐震等級1	法律のとおり
耐震等級2	法律の1.25倍の力で設計
耐震等級3	法律の1.5倍の力で設計
（免震建物は、耐震等級3に相当する）	

◎地震保険料が割引になる

耐震等級1	10%割引
耐震等級2	20%割引
耐震等級3	30%割引
（免震建物	30%割引）

出典：国土交通省「日本住宅性能表示基準」2006年改正

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伝統建築に見る耐震技術

先人の知恵に学ぶ

五重塔が地震に強いことはよく知られています。しかし、なぜ強いのかは完全には解明されていません。塔の中央にある心柱は周囲の骨組と独立しており、地震の際に別の揺れ方をして周りの骨組と干渉することで揺れを減らしていると考えられています。同じような原理が東京スカイツリーに採用され、心柱と周囲の骨組との間にオイルダンパーが設置されています。最先端の制振技術と伝統的な構法が同じ原理を採用していることは、とても興味深いものがあります。

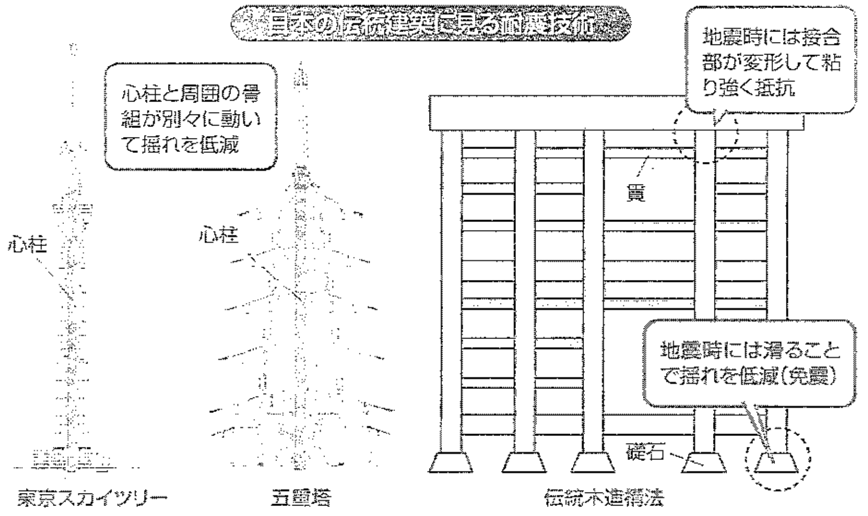
伝統的な木造建築物の基礎には、柱を地中に埋める形式（掘立式）と礎石の上に載せる形式の2つがあります。柱を礎石の上に載せるのは腐食を防ぐためですが、地震の際には礎石の上を建物がずれて揺れが減る免震の効果が期待できます。現在では、木造建築物の土台は基礎に緊結することが法律で義務付けられています。風で飛ばされることを防ぐためですが、免震効果がなくなるのは残念です。ほかにも柱を横木で貫く貫構法は、塑性変形能が大きく地震に粘り強く抵抗できるといわれています。また、京都の三十三間堂の基壇には、版築と呼ばれる砂と粘土を層状に積み上げる工法が使われています。地震の揺れを吸収する免震工法だと説明されていますが、科学的には検証されていません。

海外に目を向けてみましょう。地震国であるイランの北部には、丸太を縦横に組み合わせた基礎を持つ高床式の建築物があります。この構法は数百年前にさかのぼるといわれ、地震の際には丸太が転がって建物の揺れを減らすそうですから、立派な免震構造です。似た工夫が、やはり地震国であるアルジェリアにもあります。首都アルジェの旧市街地カスバにある18世紀の寺院には、地震力を減らすために煉瓦造のアーチと柱との間に木造の丸太が差し込まれています。

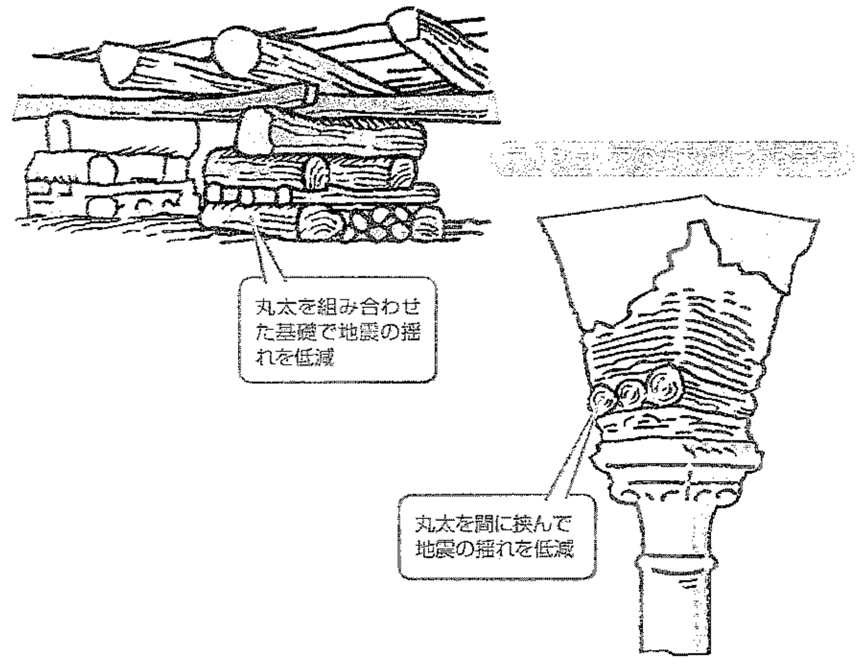
度重なる地震を生き延びてきた伝統建築には、先人の知恵と工夫があります。

- ●五重塔と東京スカイツリーは心柱制振
- ●伝統的な木造建築物にもある地震に強い工夫
- ●海外の伝統建築に見られる丸太免震

日本の伝統建築に見る耐震技術



海外の伝統建築に見る耐震技術



33 建物の安全水準の決め方

総費用最小化原理とパレート最適

予測できない事象やばらつきが大きい事象を定量的に扱う目的で確率は便利な方法です。みなさんも天気予報の降水確率を参考に、外出の際に傘を持っていこうかどうかを判断していると思います。こうした判断は、傘を持つことの手間と雨に濡れずにすむ便益とを無意識に天秤にかけていることになります。

地震に対して建物をどこまで安全にするのかという問題も、手間と便益の関係で考えることができます。建物をより安全にしようとすれば、手間に当たる初期建設費用(C_I)は増加します。一方、地震による期待損失額は、地震によって建物が破壊される確率(P_I)と破壊による損失額(C_F)との積で表すことができます。この期待損失額を減らすことが便益になります。

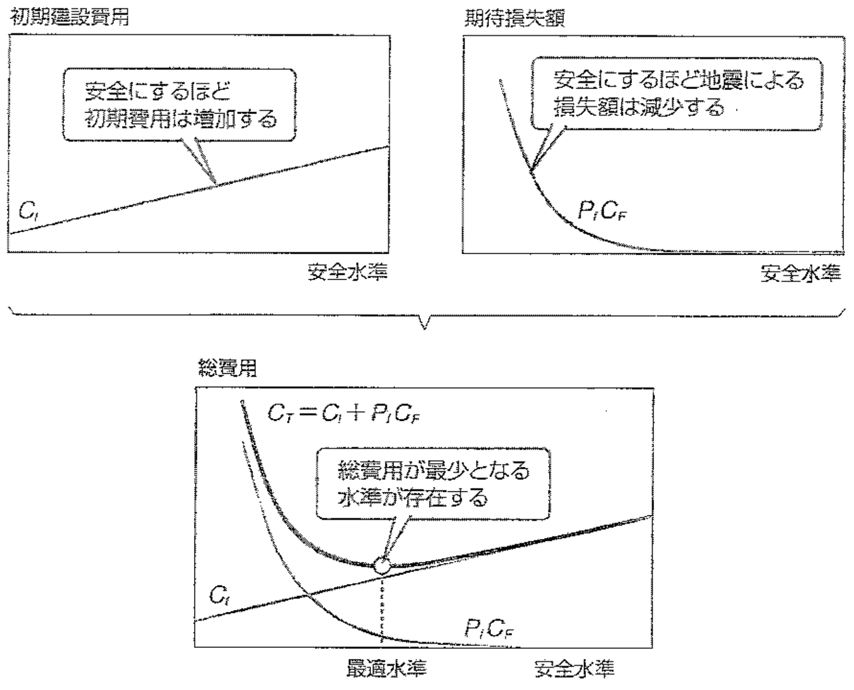
さて、建物が安全になればなるほど、初期建設費用(C_I)は増加し、期待損失額($P_I \times C_F$)は減少していきます。両者の和である総費用($C_T = C_I + P_I \times C_F$)をグラフ化すると、建物の安全水準がある値のときに総費用(C_T)が最小になることがわかります。この安全水準は、経済的に最も合理的な水準と考えられます。このようにして目標とする水準を求める考え方を総費用最小化原理といいます。

期待損失額を計算する際には、地震による建物の直接的な被害だけでなく、地震被害に伴う企業の営業停止などの二次災害も損失額に含めることができます。また、地震によるケガや人命も治療費や死亡保険金などの形で損失額に含めてしまう考え方もあります。

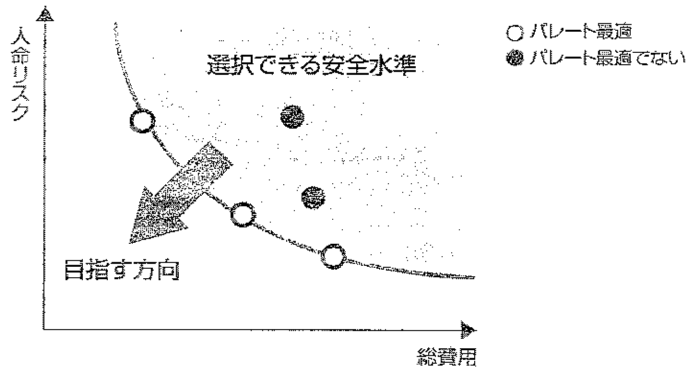
一方、人命をお金に換算することに抵抗を覚える人もいるでしょう。人命リスクを減らすことを重視すれば、経済的に合理的な水準よりも高い水準の安全性が求められることがあります。このように、人命リスクと総費用最小化という複数の目的を満足させる水準は、経済学の分野ではパレート最適といい、均衡する複数の解が存在することがあります。

要点BOX
- ●建物を地震に対してどこまで安全にするか
- ●経済的に最適な安全水準を求める総費用最小化原理

総費用最小化原理により建物の安全水準を求める



人命と費用を別に考えるパレート最適



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地震防災分野の国際協力

日本がリードする減災へ

第二次世界大戦後、世界でも最貧国の一つになった日本は、世界銀行や海外NGOなどの支援を受けて復興しました。世界銀行からの借り入れを返済できたのは1990年ですから、それほど昔ではありません。現在の日本の繁栄の基礎には海外からの支援があったことを忘れてはいけません。

地震防災も例外ではありません。1923年関東大震災では50か国以上の国々から義捐金や支援物資が送られました。1995年阪神淡路大震災や2011年東日本大震災においても、多くの国々から温かい支援を受けました。

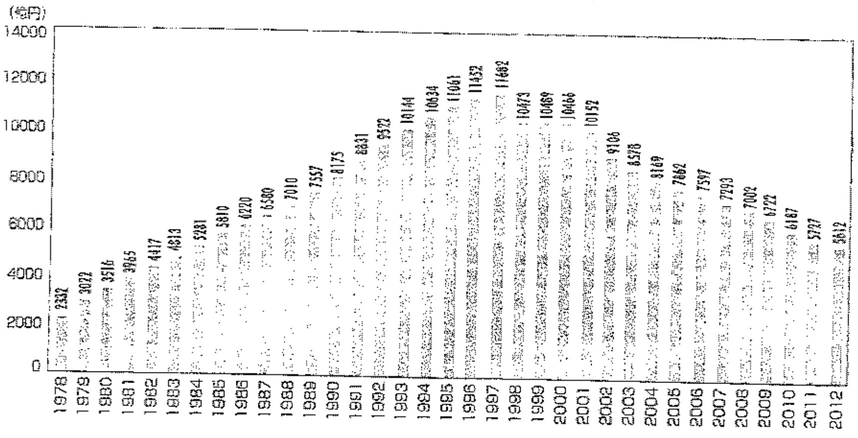
一方、日本の政府開発援助（ODA、Official Development Assistance）が開始されたのは、戦後まもない1954年です。1990年代には1兆円を超えて世界最大のODA拠出国でしたが、その後は財政難を理由に毎年予算が削減されています。日本がODAに力を入れてきた背景には、アジア諸国への戦後賠償の意味があったこと、アジア諸国の発展は貿易依存度が高い日本とっても利益になること、軍事力に代わる平和貢献であることなどが挙げられます。

ODAは大きく技術協力と資金協力（有償または無償）に分けられます。このうち地震防災分野の技術協力では、これまでにペルー、メキシコ、トルコ、ルーマニアなどで大型の技術協力プロジェクトが実施されてきました。2008年からは国際協力機構（JICA）と科学技術振興機構（JST）の共同による研究プログラム（地球規模課題対応国際科学技術協力）が実施されています。

また、防災を担う人材の育成は極めて重要です。建築研究所の国際地震工学研修は、1962年以来、50を超える国々から1500名以上の研修員を受け入れており、歴史のある研修事業です。修了生の多くは各国の防災の要として活躍し、息の長い協力が実を結んでいます。

BOX
- ●かつて日本は海外の支援を受け復興した
- ●減りつつある日本のODA予算
- ●地震防災分野の技術協力と人材育成

一般会計ODA予算の推移



出典：外務省ホームページ資料より作成

地震防災分野の主なプロジェクト型技術協力

[illegible]	[illegible]	[illegible]
ペルー	日本ペルー地震防災センター ペルーにおける地震・津波減災技術の向上	1986～1991 2010～2015
チリ	研究協力「構造物群の地震災害軽減技術」 津波に強い地域づくり技術の向上に関する研究	1988～1991 2012～2016
メキシコ	メキシコ地震防災	1990～1996
インドネシア	インドネシア共和国集合住宅適正技術開発 建築物耐震性向上のための建築行政執行能力向上	1993～1998 2007～2011
トルコ	トルコ地震防災研究センター 地震被害抑制	1993～2000 2005～2008
カザフスタン	地震防災及び地震リスク評価に関するモニタリング向上	2000～2003
ルーマニア	地震災害軽減計画	2002～2007
エルサルバドル	耐震普及住宅の建築普及技術改善 低・中所得者向け耐震住宅の建築技術・普及体制改善	2003～2008 2009～2012
ニカラグア	地震に強い住居建設技術改善	2010～2013
中華人民共和国	耐震建築人材育成	2009～2014

出典：JICAホームページ資料より作成