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"During an earthquake or strong winds, a natural response is to hold on to something. Through Sky Gardens, the three towers of the Island Tower Sky club are holding on to each other. But to achieve high levels of safety and to provide comfort for residents, various structural techniques were designed, evaluated and employed for this unique case scenario."

The Island Tower Sky Club is a 145-meter (477-foot) tall triplet-tower project in Fukuoka City on Kyūshū, the third largest island of Japan and most southwestern of its four main islands. The three slender towers are positioned with rotational symmetry and connected with each other by three individually-designed sky gardens. The project is the world's first high-rise residential project that is designed as three connected towers. Built in a seismically active region, a number of structural and vibration control strategies have been used in the 42-story project to assure a high level of structural safety and residential comfort. This paper discusses these strategies along with the results of modeled analysis and real life testing.

Figure 1. The Island Tower Sky Club © Akira Nishimura

Design process

Island Tower Sky Club is an ambitious residential project built on Island City, an artificial island reclaimed in 1994 in the Hakata Bay in Higashi-ku. This area is one of the seven wards of Fukuoka City, situated on the northern shore of the island of Kyūshū. Island City is planned as a mixture of housing, commercial and maritime activities and distribution. The conceptual design of Island Tower Sky Club included living spaces in a natural environment, a strong relationship with the sea, excellent day lighting, wide views and green space. As such, the design seeks to set a new standard for future residential developments (see Figure 1).

The initial design presented a single, 145-meter tall residential tower with 42 stories, illuminated at the top like a gigantic lighthouse to reflect the maritime character of Island City. During the second design phase, the building was divided into three equally tall towers, positioned with rotational symmetry and offering a combined floor space of 61,296 square meters (659,785 square feet). Dividing the program up into three slender towers, with a floor plan of 20 x 20 meters (66 x 66 feet) each, resulted in a slenderness ratio of 1:7 and provided for brighter living spaces and wider views. During the final design phase, three sky gardens were designed which joined the three towers on the 15th, 26th and 37th levels. The inclusion of the sky gardens offered significant green spaces as part of the building complex, provided alternative evacuation strategies and played a substantial role in vibration control strategies. Additionally, by connecting the three towers, both the lateral and torsional stiffness of the buildings were increased (see Figure 2 and 3).

The lower part of the buildings are designed as one structural element with a continuous foundation beam on top of steel tube in-situ driven concrete piles, with one continuous beam at the first floor and a continuous thick slab at the third floor in order to carry the overturning moments of each tower.

Precast and cast-in-place concrete methods were employed during the construction of the building. Aluminum moulds were used to cast the core walls and steel forms were used for the slabs. Self-standing steel stairs and sliding scaffolds were also implemented during construction. The similarity of the three towers allowed for repetitive tasks to be conducted on each tower, and the construction progressed upward in a spiral form with a rate of one story for each tower every six days.

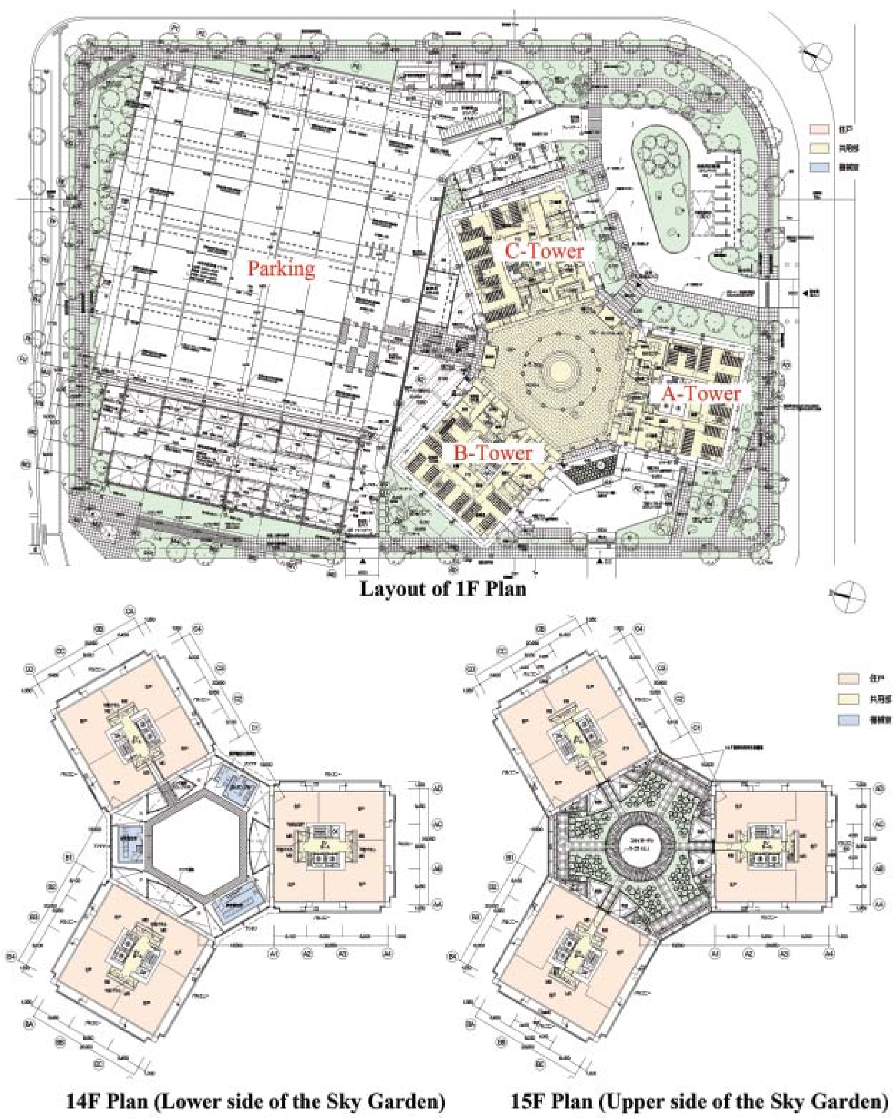

Figure 2. Typical Floor Plans © Akira Nishimura

Structural Safety

Tower Sky Club employs four primary techniques to improve structural safety during earthquakes and residential comfort during strong winds.

Super-Flex-Wall

Each tower is provided with a Super-Flex-Wall. This structural framing method combines a thick core wall with a vibration control method or with a base-isolation method. This method reduces the shaking and physical damage that could be caused during a major earthquake. The core wall of the towers in the Island Tower Sky Club is made out of high-strength reinforced concrete (70 N/mm^2 or 10,152 lbs/in^2), which is able to carry a large part of the seismic and wind loads. By locating the core wall at the center of the plan the building is well supported, and perimeter columns and beams can be progressively reduced at each higher level. This reduction of structural members allows for maximum views. Three framing plans were designed for the towers. The low-level stories have a full frame structure with internal and peripheral beams, the mid-level stories have a frame structure without internal beams, and the high-level floors have a frame structure without internal or peripheral beams and have extremely thin steel columns around the periphery (see Figure 4).

Base Isolation System

In the base of the tower complex, a hybrid isolation system was adopted to reduce the acceleration response of the building during major earthquakes. This system is composed of multi-layer natural rubber bearing supports and low friction sliding bearing supports. The bearing supports have a friction coefficient μ of 0.01 and are installed to increase the isolation period of the building. Additionally, U-shaped metallic and oil dampers were installed to absorb vibration energy (see Figure 5 and 6).

...branding

> “Designer skyscrapers are more than the physical boxes where business is performed and money is made; they constitute the symbolic infrastructure and branding for cities with global status, and they are actively welcomed by the authorities of both mature and emerging cities.”
>
> *Kathy Pain, RICS in her article "Form Follows Finances," Modus, March 2011.*

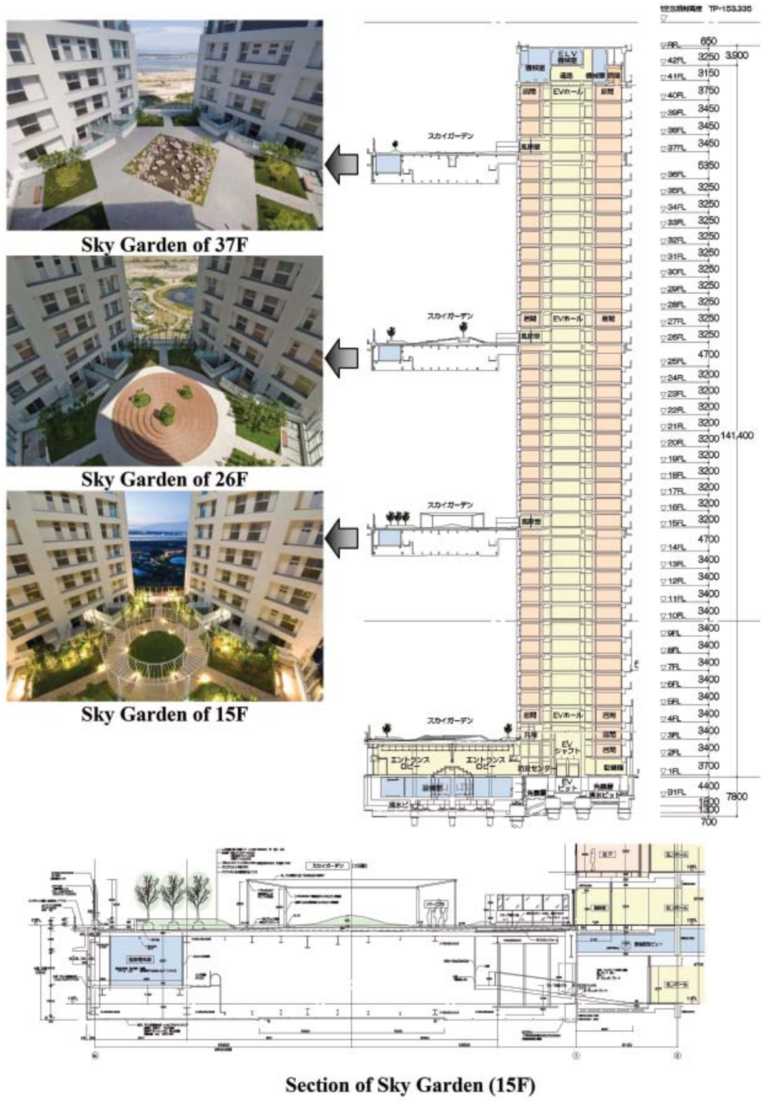

Figure 3. Typical Section and Sky Gardens © Akira Nishimura

Vibration Control System in the Sky Gardens

The towers are connected at three different levels through the sky gardens. These structures are constructed of concrete slabs supported by steel trusses. The trusses are connected to the towers with vibration control dampers to reduce the overturning effect of the towers caused by seasonal winds and large earthquake motions (see Figure 7).

The towers employ two types of vibration control dampers: oil dampers and broadband vibration control dampers (or BB Dampers). The BB Dampers are a buckling restrained hysteresis damper made of very low yield strength steel and connected in series with a laminated visco-elastic damper (see Figure 8). The ten-layer laminated visco-elastic rubbers are vulcanized with the steel plates. The thickness of each of the rubbers is 3 millimeter (0.12 inch). Two pins, with a diameter of 50 millimeters (1.97 inches), work as the stopper. Each pin penetrates the steel plates and the visco-elastic rubbers. A clearance of 1.5 millimeter (0.06 inch) separates the pin and the case. This allows the diameter of the case to be larger than that of the pin by 3 millimeters (0.12 inches). Therefore, the laminated visco-elastic damper has a damping effect within deformation limits of 3 millimeters (0.12 inches).

The buckling restrained hysteresis damper is composed of the main brace member BH-150x150x25x25 made of very low yield strength steel ($\sigma y = 100$ N/m^2) and peripheral BBox-185×185×16 (SS400) to restrain buckling of the main brace member.

The oil damper is used as a damper for earthquake motions. The maximum damping force is 1,000 kN.

For a small excitation, such as seasonal winds, the laminated visco-elastic damper reduces the response of the building. For a large excitation, such as an earthquake, the buckling restrained hysteresis damper and the oil damper reduce the response of the building. This vibration control system therefore has an effective damping system for both large and small excitations.

The most memorable event during construction was the lifting of the sky gardens. Steel trusses were prefabricated without any interruption of the construction cycle of the towers. The lowest garden was built first, on the ground, and then lift up to its designated location. From there, each higher garden was built upon a lower garden and lifted up to its designated location. To avoid

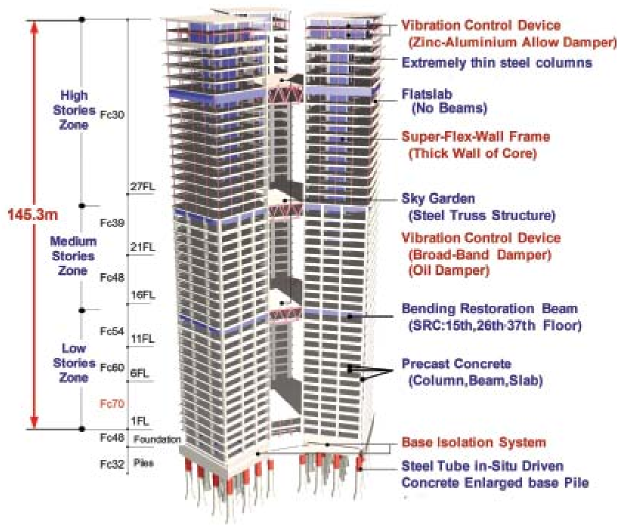

Figure 4. Outline of the Structure © Akira Nishimura

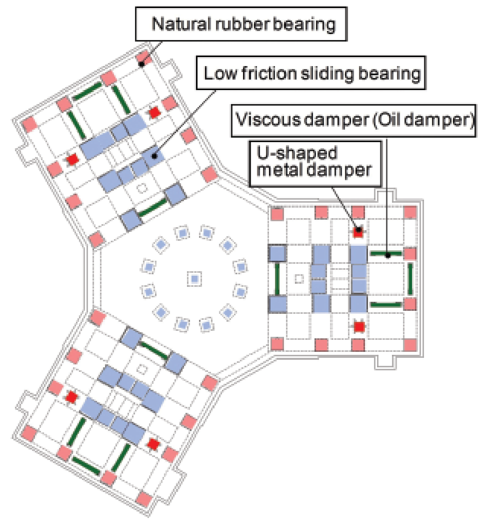

Figure 5. Layout of isolators and Dampers © Akira Nishimura

Figure 6. isolators and Dampers © Akira Nishimura

any slanting or stroke to the vibration control dampers when positioning the sky gardens, all planting and finishing of the gardens was first completed and then the vibration control dampers were fixed to the buildings.

Vibration Control System at the Two Upper Stories of Each Tower

A vibration control system with superplastic Zinc-Alminum alloy dampers (Zn-Al Damper) was adopted for the upper stories of each tower. Zn-Al alloy was selected because of its visco-elastic nature, which enables stable energy absorption in a wide range of strains. The alloy also exhibits significant resistance to fatigue, which would require no maintenance or replacement even after a major earthquake. Structural analysis has shown that the dampers would reduce earthquake-induced story drift at the top floors by up to 40%.

Seismic Response Analysis

The first step in the analysis processes of the tower's seismic response strategies was to create a full structural model, which displayed the building as designed. However, this model was too complex to be used in a parametric study of seismic response analysis. As a result, the model was significantly simplified. Each tower was modeled as a lumped mass model with shear and bending springs in two horizontal directions (see Figure 9). The sky gardens and isolating stories (i.e., the level where the isolators and U-shaped dampers are installed), are modeled by structural members to appropriately evaluate the effect of the isolators and the vibration control dampers. The first natural period* at the

* Under the existence of damping, the natural period is dependent on the amplitude of vibration. Therefore the author would like to note the amplitude at which the natural period is calculated.

velocity amplitude of 30 centimeters in the isolating layer is 6.65 s, according to the analysis using the lumped mass model.

The input ground motions for the response analyses are:

1. Three synthesized ground motions, all of which fit the spectrum stipulated in the Building Standard Law in Japan, (Artificial ground motion 1, 2, 3)
2. Three recorded ground motions that are North-South component of El Centro 1940, East-West component of Taft 1952, and North-South component of Hachinohe 1968
3. A simulated earthquake motion of the nearest fault, which is the Kego fault.

The results of maximum response are shown in Figure 10. The maximum acceptable acceleration is 200 cm/s^2, which is the motion threshold for overturning furniture. Story shears are designed to not fall below the maximum responses obtained by the analyses. The maximum displacements sufficiently satisfying the deformation criterion is 50 centimeters for isolators. The maximum inter-story drift angle to satisfy the criterion is 5.0×10^{-3} (=1/200) radian.

For a detailed investigation of structural control design, the absorbed energies are calculated using artificial ground motion 1 as input ground motion. According to the time history of absorbed energies for each element, the isolation story that is equipped with U-shaped metal dampers, oil dampers, and the friction force of low friction sliding bearings absorbs approximately 80% of the total energy absorbed. The internal viscous damping of the frame absorbs 10% of the total. The hysteric damping of the frame and the seismic vibration dampers both absorb around 5% of the total. The final result is that the seismic vibration dampers absorb one fourth of the energy of the isolated superstructure. As for the vertical input ground motion, Ishide (2009) reported that the sky gardens can reduce the vibrations by 15%.

Vibration Tests of the Towers

Vibration tests were carried out on the towers themselves to confirm the control performance of dampers in a small vibration range. The tests were conducted during two construction phases; before connecting dampers in the sky garden trusses and after connecting them. Both phases were near the end of construction, and building conditions were as close to full completion as possible. Between the two tests, no significant changes were made to the structure of the building.

First, the micro-tremor of the building, a low amplitude ambient vibration of the ground, was measured to investigate the basic vibration characteristics of the building. Second, man-made disturbances were introduced to investigate the building's damping characteristics.

Ten velocity sensors were used in these tests. The sensors were set at the B1, 1st, 14th, and 25th levels of the C-Tower (see Figure 2 and 3). The directions of the sensors were in the *x* and *y* directions as defined by the gridlines of the C-Tower. The sampling time of the measurements was 0.01 seconds.

The Fourier spectra of the building velocity were calculated using a ten-minute record of the micro-tremor with the Hanning window (a window width of 0.01 Hz). The building frequencies were evaluated based on the peaks of the spectra. Before connecting the dampers, the first resonant frequencies that correspond to swaying mode were evaluated

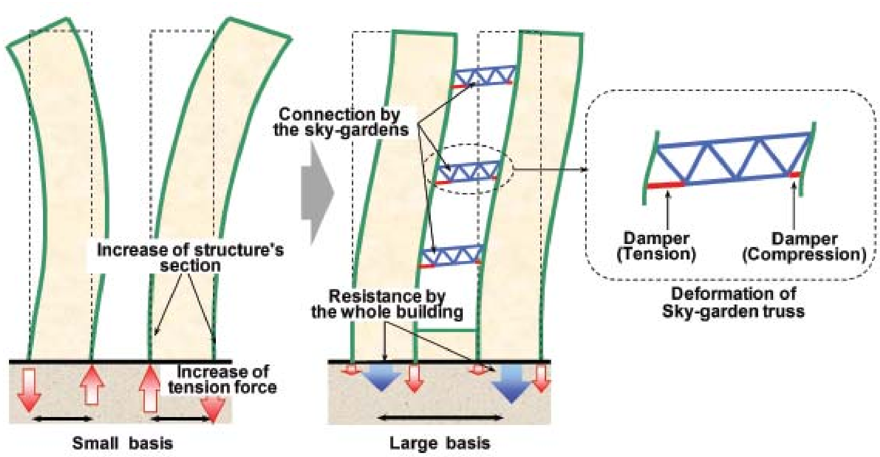

Figure 7. Control Mechanism of the Dampers in the Sky Garden Trusses © Akira Nishimura

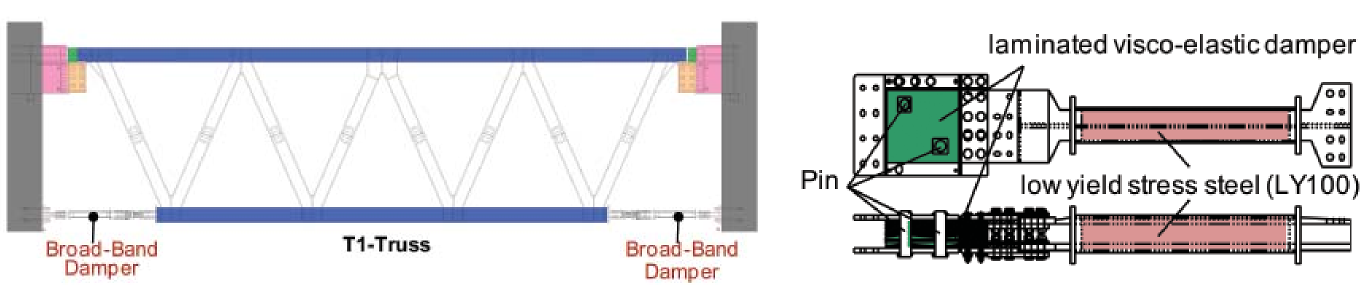

Figure 8. BB Dampers © Akira Nishimura

as 0.32 Hz for both the *x* and *y* directions. The second resonant frequency for the *y* direction that corresponds to torsional mode was 0.37 Hz. After connecting dampers, the first and second frequencies increased to 0.35 Hz and 0.41 Hz, respectively. The connections of dampers in the sky garden trusses increased the frequencies about 10% in a micro-tremor vibration level.

To investigate the vibration characteristics of the building in a larger range than the micro-tremor, human powered excitations were conducted. The tests were conducted on the sky garden at the 37th floor by approximately fifty people. The excitation frequencies were based on the results of micro-tremor and adjusted based on the excitation results.

The maximum acceleration at the 36th floor was 0.2 cm/s^2, both before and after the connection of the dampers. The modal shapes are obtained by the free vibration waves after the excitations. There were no significant differences between those before and those after the connection of the dampers. It was observed that the isolating story moved approximately 20% of the vibration at the 36th floor after this excitation.

The evaluated damping factors and frequencies of the building, relative to the building velocity, were calculated using continuous three waves taken out from the free vibration waves. The damping factors were increased by the connection of the dampers. Especially in the range of large velocities, the damping factors increased from 1.6% to 2.4%. The control performance of the dampers in the sky garden trusses was evaluated as adding the damping factor of 0.8% to as small a velocity as 0.07 cm/s.

The frequencies increased by about 6% as a result of the connection of the dampers. The frequencies therefore turned out fairly independent of the velocity of the building. ■

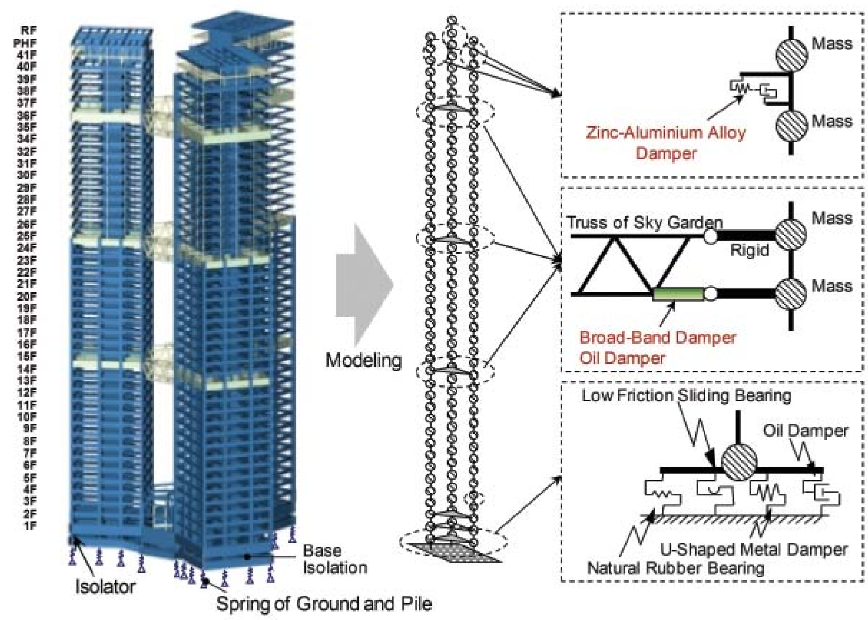

Figure 9. Analytical Model © Akira Nishimura

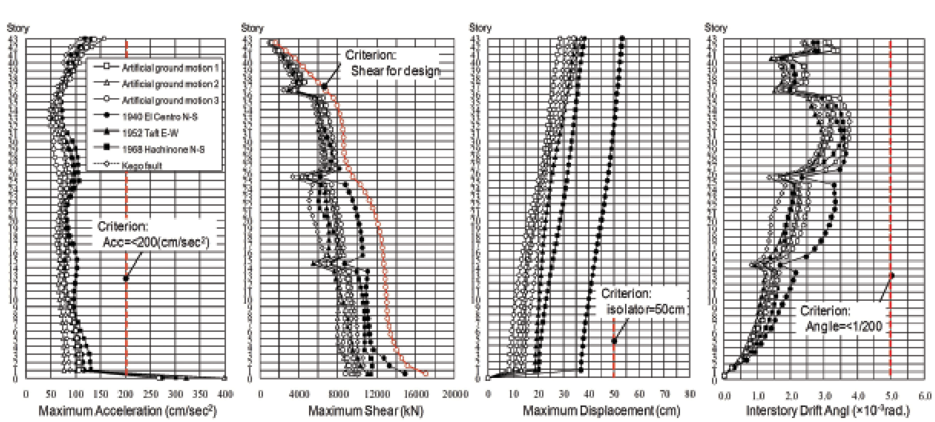

Figure 10. Results of Maximum Response © Akira Nishimura

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