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Abstract

Presented in this paper is an outline of a structural design of Tokyo Sky Tree which is a new core facility of digital broadcasting for Tokyo metropolitan area of Japan. It will be a height of 634m, double the height in Japan, and the highest tower in the world for broadcasting, when completed.
The requirements for structural designs in Japan are extremely severe, because several typhoons arrive every summer and big earthquakes occur with high probability, and consequently Tokyo Sky Tree was required to adopt high criteria, over the building regulations in Japan, because of its heavy public responsibility to send valuable information to the victims in a big disaster.
Unique systems for a vibration control, the core column system and the rigid substructure system, were invented for this tower to satisfy the requirements for structural designs.

Keywords:*broadcasting tower; aerological wind observation; wind tunnel experiment; artificial wind wave; vibration control system*

Introduction

Tokyo Sky Tree (Fig.1) is a newcore facility of digital broadcasting for Tokyo metropolitan area of Japan. It will be a height of 634m (2,080ft) and the highest tower in the world for broadcasting, when completed in the spring of 2012.

This tower is expected to be a tourist attraction, a base of broadcasting and telecommunications, a quasi-disaster prevention centre of Tokyo metropolitan area.

The requirements for structural designs in Japan are extremely severe, because several typhoons arrive every summer and big earthquakes occur with high probability, and consequently Tokyo Sky Tree was required to adopt high criteria, over the building regulations in Japan, because of its heavy public responsibility to send valuable information to the victims in a big disaster. On the other hand, the structural characters of this tower are deferent from the other domestic structures, and then a new design method had to be invented especially for the earthquake and the wind resistant design.

Figure 1. Tokyo Sky Tree (Oshiage in Sumida ward, Tokyo, Japan)

Unique systems for a vibration control, the core column system and the rigid substructure system, were invented for this tower to satisfy the requirements for structural designs. Generally steel towers have poor damping capacity, and improvement in damping ability is demanded for this tower. The core column system uses the core shaft of an emergency staircase built with a reinforced concrete tube wall as a weight, using the theory of TMD, tuned mass damper. Rigid substructure system uses the wall piles, thickness is 1.2m and depth is 35m over the bearing stratum under the surface soft ground, and using a relative displacement between the soft ground and the rigid substructures to gain the damping ability.

Superstructure

This tower varies in silhouette with a view point, according to the alteration of plans, the bottom floor is a triangle and the observatory floor is a circle (Fig.2).

Steel structures with pipe truss are adopted to decrease weight, and not to pressure residents around. A circular section pipe has the advantage of fabrication and welding compared with a box section pipe, and make possible roundish silhouette.

The maximum strength of pipe is 630N/mm2 and the maximum diameter is 2300mm, and the maximum thickness is 100mm (Table 1). A frequency of each member is designed large enough not to occur the vortex induced vibration up to the strong wind L3(Table 2:return period is 2000 years).

Table 1 : Maximum size of steel pipe (high performance steel)

Type	Strength (N/mm2)	Maximum Diameter (mm)	Maximum thickness (mm)	Height (m)
630N/mm2 Class	630	1200	80	500
500N/mm2 Class	500	2300	100	0
400N/mm2 Class	400	1900	60	20

Substructure

This site is located in the bank of the Sumida River and its surface layer is occupied with silt, extremely soft ground. A RC wall pile is adopted as basement (Fig.3: yellow panel), thickness is 1.2m and depth is 35m, and stands on the bearing stratum under surface soft ground. This is one of strategy for seismic design, the rigid substructure system. This system constitutes of a rigid wall pile and soft ground, and makes use of a relative displacement between the rigid substructures and soft ground to gain damping ability, the radiation damping. But this effect can't easily grasp, and the measurement of both behaviors during the earthquake will demonstrate the effect after completed.On the other hand, the foundation (Fig.3: blue structure, abutment) was required to secure not only horizontal but also vertical rigidity, and the ability of pull-out resistance, because of the weight saving of superstructure. A comparative study in the foundation system of this tower was executed, and finally two plans were compared thoroughly. The counterweight plan (Fig.3: left plan) uses the weight of foundation as pull-out resistance and constructs on pneumatic caisson method.

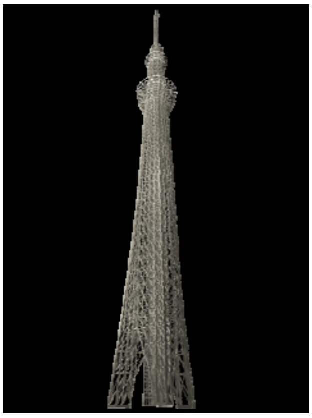
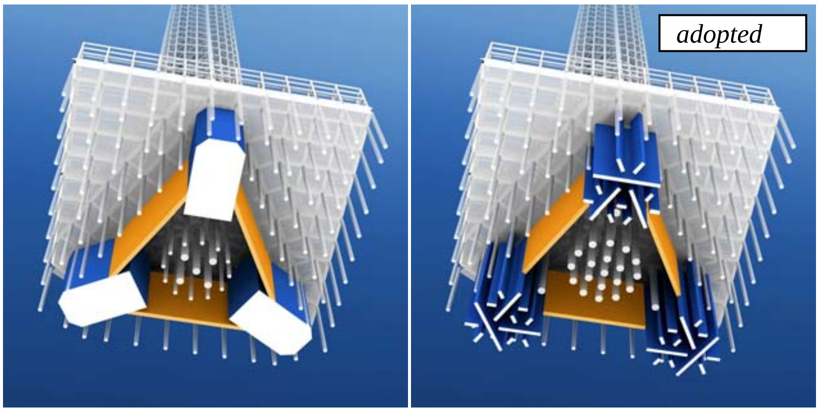


Figure 2 Superstructure



Counterweight plan SRC(bl.)and RC(ye.) wall pile plan

Figure 3 : Plan for Substructure

The wall pile plan (Fig.3: right plan, adopted) uses the weight of soil grasped by foundation as pull-out resistance, using the friction of the pile surface. The counterweight plan is simple and reliable system compared with the wall pile plan. But wall pile plan was adopted in the basic design, because it excels at the adjacent construction near the subway.
The aspect ratio of Tokyo Sky Tree is about 9.0, and the top displacement is too large to broadcast if the foundation has poor vertical rigidity because of the uplift-rocking deflection of Foundation. For example, 10.0cm displacements of a pile convert 90.0cm displacements at the top of the tower. A SRC pile (steel reinforced concrete pile, concrete encased steel pile) was adopted as the foundation structure to consider the continuity of steel member as the steel tower. However, behaviours of SRC pile under the pull-out force depend upon the amount of cracks, the pull-out test with actual size test model indispensable for the stability and reliability of the tower during the strong wind and the earthquake. The pull-out test, the maximum load was 40,000kN, executed in the site preceded the design.

Assumed disturbance

The in-service period to decide the disturbance for the structural design of this tower is 100 years, and it is longer than that an average building sets up in Japan, because this tower is expected to be a quasi-disaster prevention centre of Tokyo metropolitan area. In addition, this tower has L3 level criteria defined with the return period of the disturbance that the building regulations in Japan don't require, and that afford to resist the big disaster that no one expected (Table 2). The L3 level assumes the earthquake that supposes the activity of the hidden faults. There are many faults already investigated in Japan, but a small earthquake under M6.9 doesn't leave a track on the grand surface, and this criterion assumes an existence of such a hidden fault just under this site. This assumption, the scale of the hidden fault M6.9, is offered from Japanese government, and geological survey verifies no fault exist just under this site.
The structural safety limit according to the L2 disturbance for this tower is almost no damage, and it is the criteria to continue the broadcasting and to support the revival of victims in the big disaster, and the L2 disturbance is the maximum level that the building regulations in Japan require to the domestic buildings.
The regulations for the velocity of vibration in the frequent wind were established for the gain tower, the top o f the tower and the antennae for broadcasting are installed.

Table 2 : Design Criteria

Level	Standards of do mestic law	Specification of design for disturbance	Structural safety limit
L１	Rare	Strong wind : Return period= 100 years Earthquake : middle	No damage
L２	Very rare	Strong wind : Return period=1350 years Earthquake : Big	Almost no damage
L３	Unexpected	Strong wind : Return period=2000 years Earthquake : Hidden faults	Elastic behaviour

Characteristics of aerological wind

The structural design of this tower is especially decided with wind induced response rather than seismic response. It is most important for wind resistance design to define wind profile of average wind velocity, the wind profile, from the ground to the top of this tower. Wile, the development of boundary layer wind depends on the surface roughness of windward side ground as shown in Fig.6.

Then observation of aerological wind over this site was an essential condition to know the characteristics of wind and to do wind resistant design of this tower. A wind profile was inferred to define with power law from previous studies, but no one knew a height of wind in gradient-wind-balance over this site.

At first the observation of aerological wind was planed by wind profiler and GSP sonde(Fig.4, Fig.5). Wind profiler is an instrument to observe aerological wind velocity using a sound wave, but the sound is too noisy to use in downtown. Then, there was no help only to use GPS sonde. The way uses the balloons that fly with wind and inform it's position a second by GPS to the base, and wind velocity can be easily known.

The 50 balloons were launched from the roof of building near this site, and the phenomenon was observed that an average wind velocity was constant from 1000m to 1300m. It is difficult to define the height of wind in gradient-wind-balance because the numbers of observations were too little to estimate, but from this research it is concluded to accept power law under a height of 634m the top of this tower to define the wind profile for wind resistance design.

Figure 4 : Balloon-launching system

Figure 5 : Observation of wind with GPS sond
e

This site located in downtown Tokyo, but the surface roughness for wind resistant design is the same one for bay area. Because enough distance from the coast is needed to develop the boundary layer up to the top of this tower, and this site is not only 8km away from the coast.

The turbulence effects within the atmospheric boundary layer are extrapolated from previous studies.

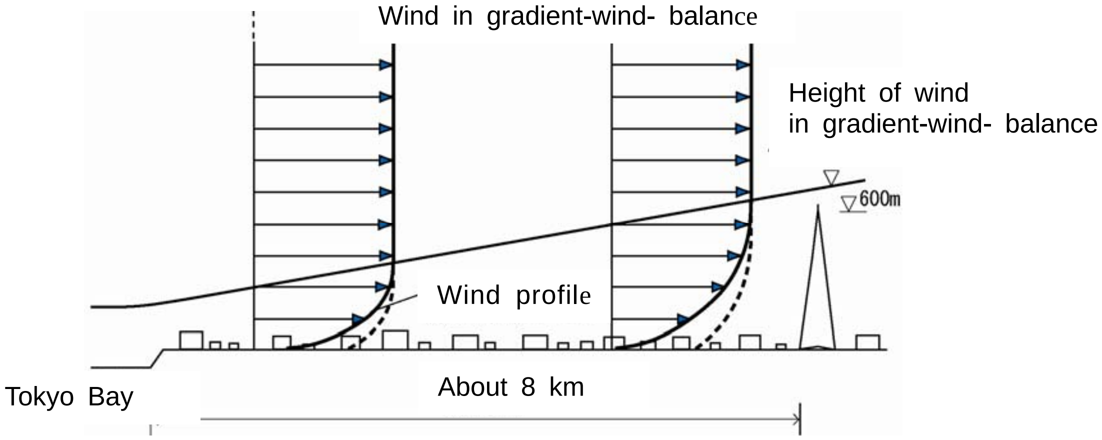


Figure 6 : Notion of the boundary layer

Verification of structural safety for wind response

（1） Set the characteristics of natural wind （Verification with statistical methods）

- A height of wind in gradient-wind-balance over this site is defined according to the observation of aerological wind. Power law is adopted to define wind profile under a height of 634m.
- The turbulence effects within the atmospheric boundary layer are extrapolated from previous studies.
- These processes are the verification with statistical methods.

（2） Time history response analysis in a strong wind （Logical simulation）

- Time history response analysis is executed to verify the wind response, the safety of the members, the effect of vibration control system, fatigue failure of welding, et cetera with logical simulation.

（3） Boundary layer wind tunnel simulations (Physical simulation）

- The boundary layer wind tunnel simulations are executed in the airflow which is generated with obs ervation over this site. Aerodynamic force balance tests, aerodynamic vibration tests, full elastic model tests, et cetera are executed to verify the wind response of this tower with physical simulation.
- The materials to create an artificial wind fluctuation data is secured from these tests.

Figure 7 Flow of the wind resistant design

Figure 8 : The entire wind tunnel test

Figure 9 : The wind tunnel test for portion

The boundary layer wind tunnel simulations are executed that simulate behaviours of this tower against the airflow which is generated as natural wind observed over this site, and the wind response is directly verified in this experiments(*Fig.8, Fig.9*). The stability and wind response are analyzed by time history response analysis with artificial wind fluctuation data simulated the result of the wind tunnel tests.

Artificial wind fluctuation data is created targeting for the power spectral density of fluctuation components obtained by overturning moment of the base level in wind tunnel experiments, and this is one of the Monte Carlo simulations (Fig.10). It is possible with this analysis to verify the safety of members, the effect of vibration control system, the fatigue failure of welding, et cetera. The procedure of the wind resistant design developed for this tower shown in Fig. 7.

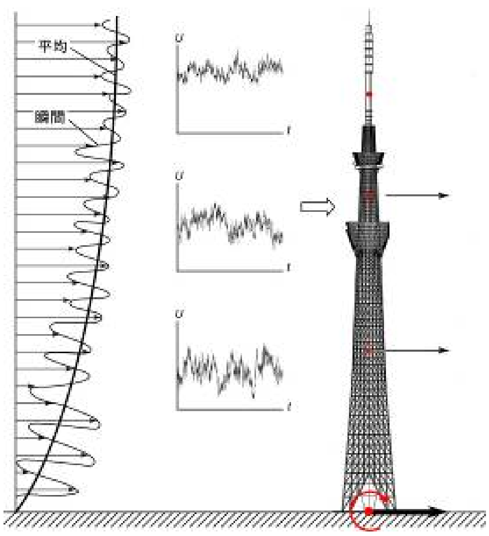


Figure 10 : Time history response analysis with an artificial wind fluctuation data

Seismic design

The predominant periods of body wave in Kanto basin spread out around Tokyo City are about a range of 2 to 9 sec, and in this site the first natural period of sedimentary stratum over seismic bedrock was turned out to be about 8 sec because of it's thickness of 2.5km according to public investigations.

On the other hand, the first natural period of this tower was inferred to be about 10 sec in the consideration of basic concept. Therefore, the seismic resistant design of this tower had to face the problem of long period ground motion fully. That is to say the problem of resonation, ground's natural period 8 sec is close to superstructure's one 10 sec. The array microtremor survey was conducted in this site, in order to define and to be accurate the shear wave velocity structure of sedimentary stratum. The reliability of seismic stability depends on the accuracy of the design earthquake ground motions, and it is created from the result of the accurate investigation.

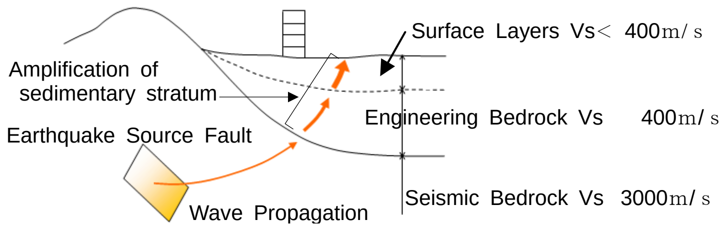


Figure 11 : Notion of the design earthquake ground motions

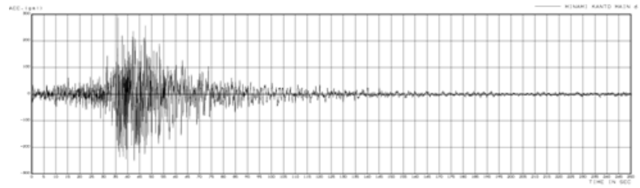


Figure 12 : Example of design earthquake ground motion

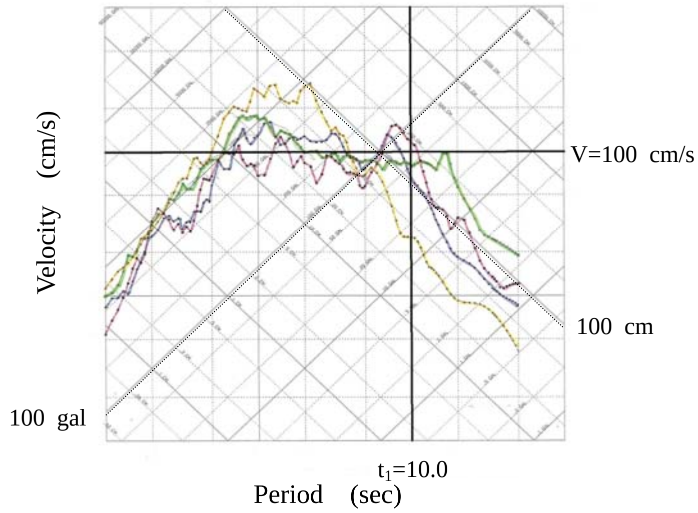


Figure 13 : Response spectrum of typical design earthquake ground motions(Log tripatite plot)

Outline of the vibration control system

The structural design of this tower, for example the decision of the member's section, is especially decided with wind induced response rather than seismic response. But it was clarified in basic concept that acceleration during the earthquake is too large to operate the instrument for broadcasting if the damping ability doesn't be added as the vibration control system. Indeed, this tower has a wide observatory and heavy weight compare with the common steel tower, but most serious reason is that the great part of wind force is a average constituent, and the reduction of the wind response with the vibration control system can not be expected enough.

Unique systems for vibration control, the core column system and the rigid substructure system, were invented for this tower to satisfy the severe requirements. Generally, steel towers have poor damping capacity, and improvement in damping ability is demanded for this tower.

The core column system uses the core shaft of the emergency staircase built with a reinforced concrete tube wall as a weight applying the theory of TMD, tuned mass damper.

The rigid substructure system constitutes of a rigid wall pile and soft ground, and makes use of a relative displacement between the rigid substructures and soft ground to gain damping ability, the radiation damping. The detail of this system described at the section of substructure.

TMD of the top

The gain-tower, a top of this tower, has to be control wind response to ensure the reliability of broadcasting. To be concrete, velocity response against a dairy wind has to be controlled under constant revel required as a new digital broadcasting tower. Two TMD system is installed at the top of this tower, upper one is 25t and lower one is 40t a weight.

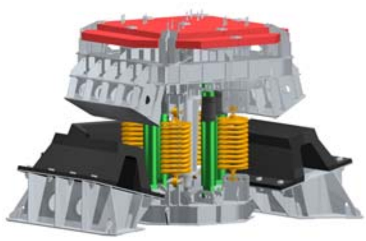


Figure 14: TMD of the top

The response control system with the core column

The core column system, a unique vibration control system using core shaft as an added mass, is developed for this tower (Fig.10, 11). The core column is a circular cylinder of reinforced concrete, and has a diameter of 8.0m, a thickness of 600cm, a height of 375m. The top of the core column is free from a main steel-frame of the tower and the upper half is connected with oil dampers, the under half is connected with steel members. Therefore, it is a column but independent of the tower and doesn't support the tower's weight.
This vibration control system is effective in the wide range and a lot of kind of earthquake. It can reduce maximum 50% the acceleration response during the earthquake and maximum 30% during strong wind.

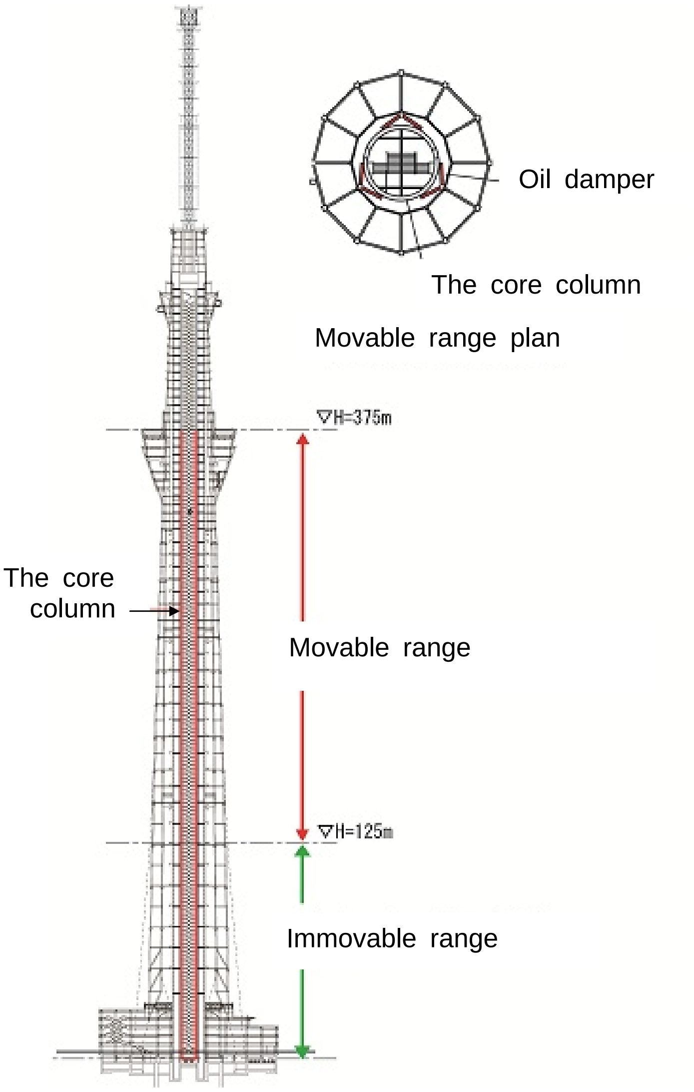


Figure 15 : Notion of the response control system

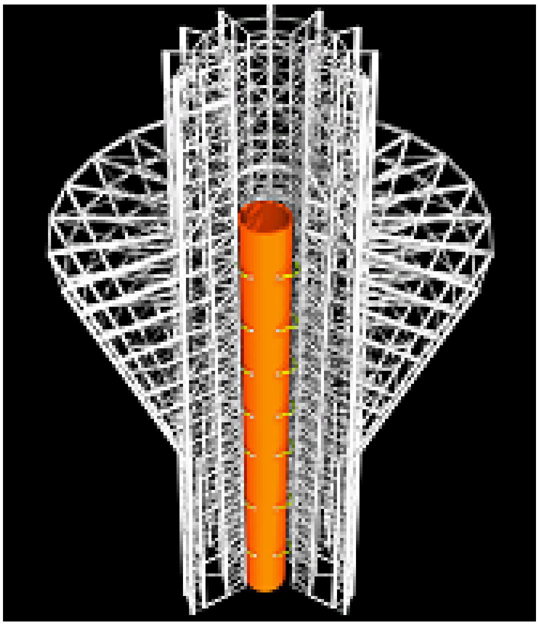


Figure 16 : Section of the core column

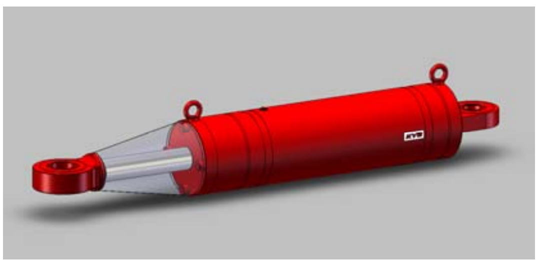


Figure 17 : Oil damper

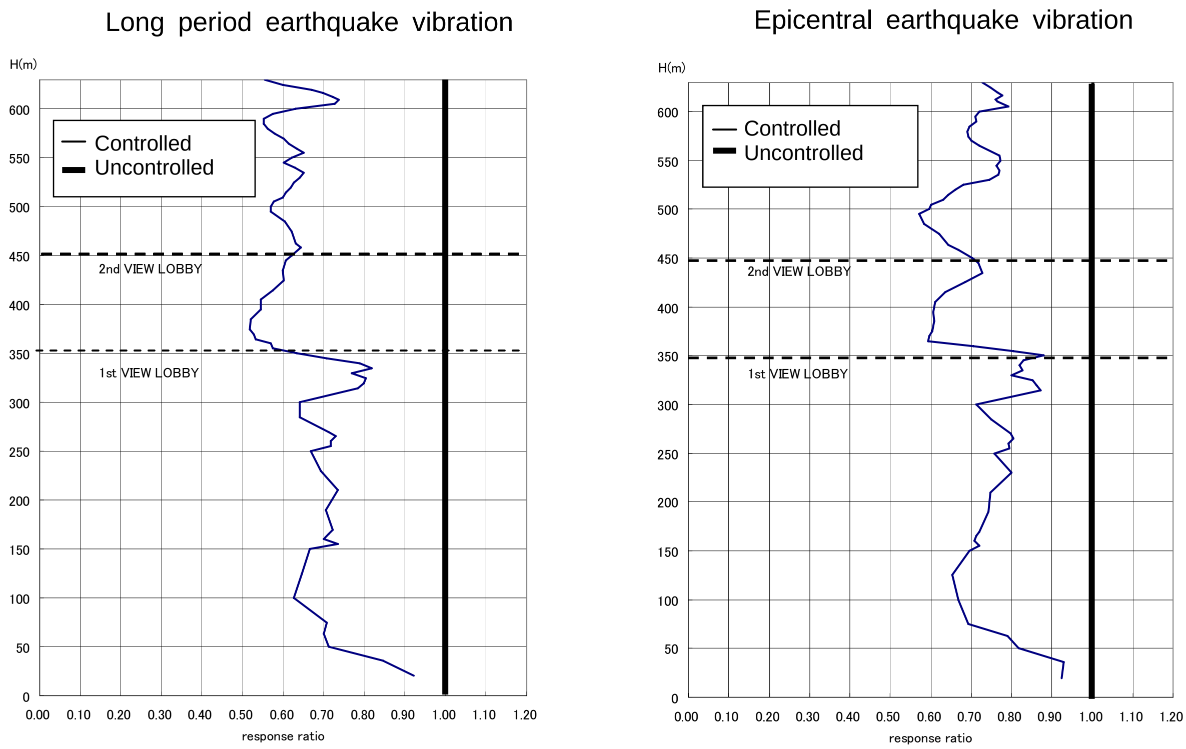


Figure 18 : Vibration damping effect of the core column system (response acceleration)

Conclusions

Tokyo Sky Tree is a new core facility of digital broadcasting for Tokyo metropolitan area of Japan, and it is re quired high criteria because of its heavy public responsibility to send valuable information to the victims in a big disaster.

The maximum disturbance for the structural design is the strong wind that wind speed is 83m/s at the top of t his tower, and the big earthquake that the response spectrum is over 100cm/s (h=5%) at the natural period o f this tower, and the structural safety limit according to L2 disturbance, the maximum level that the building re gulations in Japan require to the domestic buildings, is almost no damage.

Unique systems for vibration control, the core column system and the rigid substructure system, were invented for this tower to satisfy the severe requirements. The core column system uses the core shaft of the emergency staircase built with a reinforced concrete tube wall as a weight applying the theory of TMD, tuned mass damper. This vibration control system is effective in the wide range and a lot of kind of earthquake. It can reduce maximum 50% the acceleration response during the earthquake and maximum 30% during strong wind. The rigid substructure system constitutes of a rigid wall pile and soft ground, and makes use of a relative displacement between the rigid substructures and soft ground to gain damping ability, the radiation damping.

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