EARTHQUAKE RECORDS OBSERVED IN TALL BUILDINGS WITH TUNED PENDULUM MASS DAMPER

Tadashi NAGASE[1]

SUMMARY

A new damper to reduce the lateral vibration of buildings has been developed and installed in tall buildings in Japan, two office buildings and one hotel building. The damper is of a pendulum-type tuned mass damper (TMD), and the ice thermal storage tanks or the elevated water tank are used as the moving mass of the damper. The TMD is the most successful damper against swaying of buildings in high wind, the TMD system in a high-rise building needs a huge mass and a large room for installation at the top floor of the building, causing extra production cost and storage space problems. A solution to these problems is the tuned pendulum mass damper using the huge tanks located at the rooftop of the building as the pendulum mass weight. The damper of this type needs neither additional mass nor space because the building equipment is integrated into the damper.

This paper presents three buildings with the pendulum mass damper using equipment tanks for ice thermal storage or water supply and discusses some intrinsic features of the damper and demonstrates how simple and practical the damper is. Typhoon records observed in the buildings with the pendulum damper prove that the TMD increases the damping ratio of the building to critical from 1% to 4% or more and lessens the building vibration by 50%. Earthquake records and simulation analysis indicate that the damper cannot decrease the building responses during the main shock of the earthquake ground motion but can suppress the growth of the building's motion quickly after the main shock. It should be also emphasized in the earthquake response analysis of the hotel building that the TMD for torsional vibration reduction divides the original coupled modes of torsional translations into torsion and translation and can improve the response behaviors.

INTRODUCTION

The passive-type damper based on the classical theory of tuned mass damper (TMD) in mechanical engineering was proved to be practical and successful to high-rise buildings by the Citicorp Center in New York [4] and also by the John Hancock Tower in Boston [2] in the late 1970s. The purpose of the TMD is to reduce the building motion caused by strong winds, improving the human discomfort or solving the structural problems. The application of TMD to building structures in Japan began in observation towers in 1980s [3,11] and developed rapidly into high-rise buildings in 1990s [6,8]. Various types of dampers such as passive, active, semi-active and hybrid dampers have been devised, and now most of the high-rise buildings completed after 1990 in Japan have some damper to decrease the building motion.

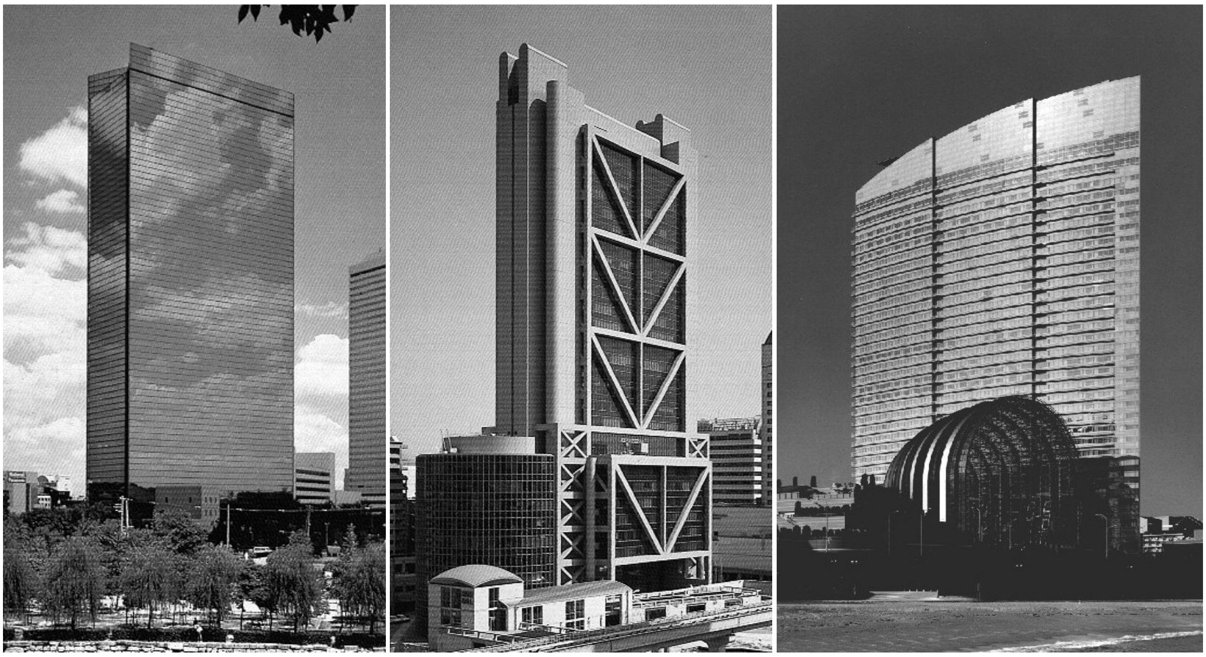
Though the TMD is the most successful damper against swaying of buildings in high wind, the TMD system in a high-rise building needs a huge mass and a large room for installation at the top floor of the building, causing extra production cost and storage space problems. A solution to these problems is the tuned pendulum mass damper using the building equipment such as ice thermal storage tanks or water supply tanks as the pendulum mass weight. The ice thermal storage tank contains liquid ice and is used for the cooling of refrigerant in a new

[1] *Building Design Department, Takenaka Corporation, Osaka, Japan email: nagase.tadashi@takenaka.co.jp*

air conditioning system, which makes the best use of low-cost off-peak nighttime electric power service. The total volume of the ice thermal tank is proportional to the building area to be air-conditioned, e.g., 0.01 to 0.02 m^3/m^2. Assuming that the weight of steel high-rise buildings above the ground is approximately 0.7 to 0.8ton/m^2 and the 70% area of the building floor is air-conditioned using ice thermal storage system gives the weight ratio of the ice thermal tanks to the building as follows: 0.7(0.01 to 0.02)/(0.7 to 0.8)=1/100 to 1/50. So the tank weight in general will amount to some one or two percent of the whole building weight. The ice thermal tanks are also used as the moving mass in the active mass damper system.

Figure 1 and Table 1 demonstrate the three high-rise building with the tuned pendulum mass damper using equipment tanks for ice thermal storage or water supply. The 37-story Crystal Tower in Osaka completed in 1990 is the first high-rise building with a TMD in Japan and the first in the world to use a pendulum for this purpose. This building is designed as a landmark tower for the area of Osaka Business Park, and the east and west elevations are very slender like a tower. In addition to the slenderness, a new air conditioning system developed for Crystal Tower requires that the huge mass of the ice thermal tanks be placed at the top of the tower. The new damper has been installed in this slender and top-heavy tower satisfying architectural and mechanical requirement ensuring human comfort in spite of strong winds.

The second tower, the 31-story P&G Japan Headquarters, constructed in the reclaimed island near Kobe in 1993 also uses the ice thermal tanks at the rooftop floor as the damper to reduce the building motion due to the strong sea winds.



(a) Crystal Tower *(b) P&G Japan Headquarters* *(c) Sea Hawk Hotel & Resort*

Figure 1: Three buildings with pendulum mass damper using equipment tanks

Table 1: Buildings with tuned-pendulum mass damper using ice thermal tanks or water tank

Name		*Crystal Tower*	*P&G Japan Headquarters*	*Sea Hawk Hotel & Resort*
Location		Osaka	Kobe	Fukuoka
Completion year		1990	1993	1995
Principal uses		Office	Office	Hotel
Number of floors		37F	31F	36F
Maximum height		157m	131m	143m
Weight above ground		44000tons	27000tons	42000tons (above 7F)
TMD	TMD tanks	Ice thermal storage tanks	Ice thermal storage tanks	Elevated water tank
	Mass weight	6@90ton=540tons (NS dir.:360tons, EW dir.:180tons)	3@90ton=270tons (EW dir.:180tons, Torsion: 90tons)	132tons (varies between 112tons and 132tons)

The 36-story Sea Hawk Hotel & Resort was completed in 1995 in Fukuoka as the third building with the damper. The water tank unit of 132 tons is used as both the building water service and the mass damper. The tower building of Sea Hawk Hotel & Resort has ship-shaped plan figure with its sharp bow heading forward the ocean. The height and shape of the tower make the bow top of the tower easy to swing against strong winds from the ocean. Since it is expected that the wind blows once a year with a maximum 10-minute average speed of 24 m/s at the top height of this building, the TMD is introduced to lessen the torsional vibration of the tower assuring the human comfort during strong wind.

2. PENDULUM DAMPER USING WATER TANK

Figure 2 sketches a conceptual diagram of the tuned pendulum mass damper. The ice thermal storage tanks or the water tank is hung from the topmost story girder forming a pendulum. The system exerts a passive type of control which needs no energy supply to actuate the damper. The TMD using the ice thermal storage tanks or the water tank as the pendulum weight presents a two-degree-of-freedom system whose fundamentals are coupled by those of the pendulum and the sloshing of the tank water. As the liquid ice or slush contained in the ice thermal storage tank behaves just like the water as long as it can move [5], the same sloshing model [1] is applicable to both the ice thermal tank and the water supply tank. Further consideration must be paid to the water volume in the tank. While the contents in the ice thermal tank does not vary, the volume in the water supply tank increases and decreases somewhat during the water service.

Figure 3 illustrates how the frequency and volume of the sloshing water affect the fundamentals of the TMD. It is indicated that when the sloshing frequency is kept higher than the twice of the pendulum frequency, the TMD fundamental will agree with the pendulum frequency and will be little affected by the practical variation of water volume in the tank. In the design of the water tank, the tank width in the moving direction must be short enough for the sloshing behavior no to deteriorate the effect of the pendulum damper. The dimension and layout of the equipment tanks for pendulum mass weight are sketched in Figure 4. Since the equipment tanks sway forth and back, special consideration must be paid to the connecting pipe joint between the tank and the building. The TMD of this type is to be locked when the sway amplitude exceeds an allowable limit, 25cm for Crystal Tower and 20cm for P&G and Sea Hawk Hotel, and will be effective against the strong wind expected up to every 20 years or so.

3. TYPHOON AND EARTHQUAKE RECORDS

The typhoon and earthquake observations in Crystal Tower and Sea Hawk Hotel & Resort are started just after the building was completed while the observation in P&G Japan Headquarters began after 1995 Hyogoken-Nambu Earthquake. Table 2 summarizes the observation records [6,9,10]. Three observation results, a typhoon record and two earthquake records observed in Sea Hawk Hotel & Resort and Crystal Tower are demonstrated in the following.

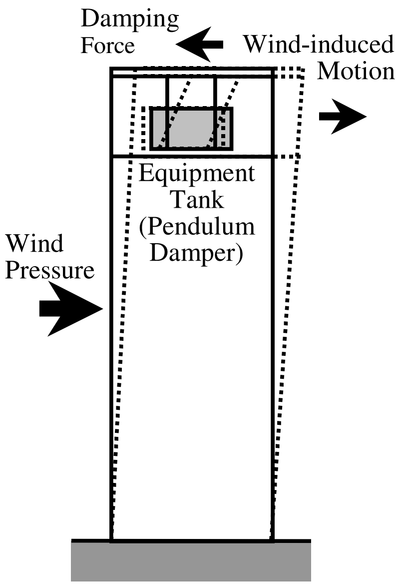
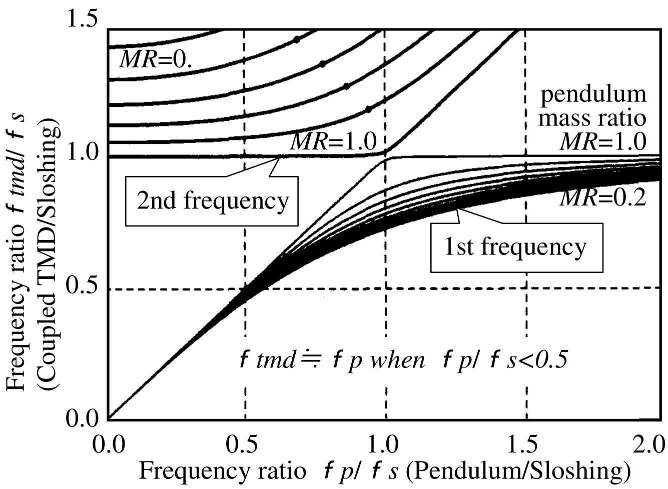
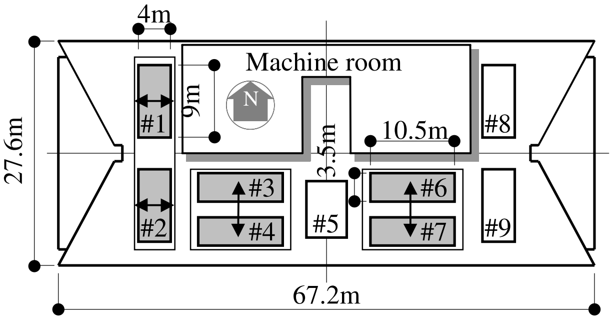


Figure 2: Conceptual illustration of tuned pendulum mass damper using equipment tanks



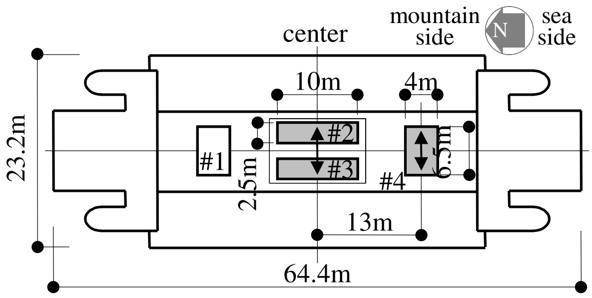
Pendulum-sloshing TMD has two frequencies. The sloshing frequency must be greater than the twice of the pendulum frequency. The TMD is not a sloshing damper and the sloshing behavior should be suppressed.

Figure 3: Coupled frequency of the pendulum TMD with tank sloshing



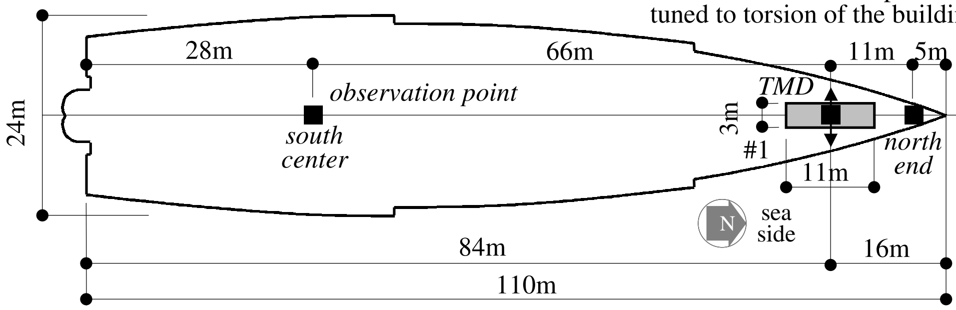
(b) Crystal Tower

Nine tanks for ice thermal storage are located on the roof floor and each weighs 90 tons. Two tanks (#1 and #2) slide in EW direction and four tanks (#3, #4, #6 and #7) slide in NS direction. Tanks #5, #8 and #9 are not used as TMD.



(b) P&G Japan Headquarters

Each ice thermal storage tank weighs 90 tons. Three tanks of #2, #3 and #4 slide in EW direction. The first mode of pendulum-sloshing of tanks #2 and #3 is tuned to EW translation while the second mode of pendulum-sloshing of #4 is tuned to torsion of the building [7].



(c) Sea Hawk Hotel & Resort

Elevated water tank of 132 tons sways in EW direction. Pendulum is tuned to the torsional motion of the tower.

Figure 4: Layout of the ice thermal storage tanks and the elevated water tank

Table 2: Typhoon and earthquake records in buildings with tuned-pendulum mass

Name		*Crystal Tower*		*P&G Japan Headquarters*	*Sea Hawk Hotel & Resort*	
Ty-phoon	Year and No.	1990 No.19		1996 No.12	1995 No.12	1996 No.12
	Maximum wind speed (tower top)	39m/s		36m/s	21m/s	51m/s
	TMD drift	4cm		4cm	3cm	17cm
	Motion reduction	50%		50%	50%	50%
Earth-quake	Year Month Day	1990.9.24	1995.1.17	1995.1.17	1996.10.19	
	Ground Acc.	7cm/s^2	205cm/s^2	no record	3cm/s^2	
	TMD drift	1cm	25cm	20cm	6cm	
	Reduction	damp quickly after Earthquake	TMD locked*	TMD locked*	damp quickly after Earthquake	

* To protect the flexible pipe joint connecting the tank and the building, the TMD are restricted to sway within a half amplitude of 25cm (Crystal Tower) or 20cm (P&G, Sea Hawk).

3.1 Typhoon 9612 in Sea Hawk Hotel & Resort:

The big and strong typhoon 9612 (No.12 in 1996) hit Japan on 14 August through 15 and challenged Sea Hawk Hotel & Resort. Figure 5 diagrams the path of the typhoon. As illustrated in Figure 6 the peak wind velocity of the 10 minute average observed at the height of 144 m above the ground was 39.2 m/s that is equal to the strong wind speed expected every 20 years. The north end motion was more than three times as large as the south center motion because of the torsional vibration. The damper worked for ten hours from eight in the morning to six in the evening with the peak amplitude of 16.9 cm. Figure 7 shows the relation between the acceleration at the north end and the amplitude of the TMD. It should be emphasized that the damper started moving when the acceleration at the rooftop reaches a mere 1 cm/s^2, proving that the frictional coefficient on the pendulum is 0.001 and the slightest sway of the building gears the device into action.

The effect of the TMD can be examined by the spectral analyses of the observed motions at the north end as demonstrated in Figure 8. The damping ratio of the tower was calculated at 1.1 % critical through the acceleration power spectrum observed in the weak wind when the TMD did not work, while the damping ratio was 4.7 % critical in the typhoon 9612. So the TMD enlarged the damping of the tower approximately four times. As the amplitude of the wind-induced vibration is inversely proportional to the square root of the damping ratio, it is concluded that the TMD can lessens the building response in strong winds by 50%.

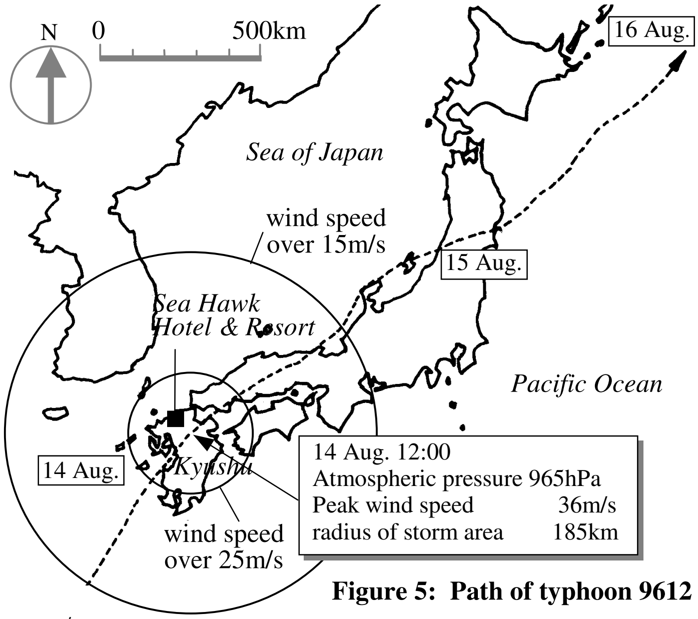


Figure 5: Path of typhoon 9612

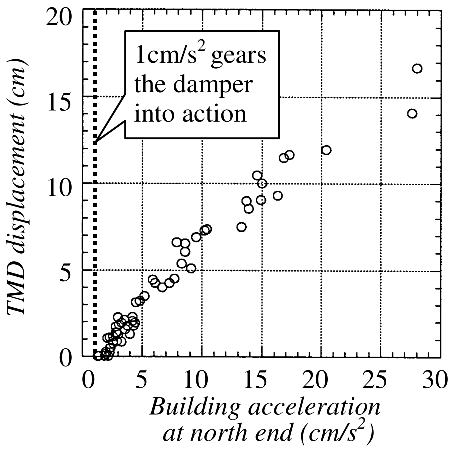


Figure 7: Relation between building acceleration and TMD displacement

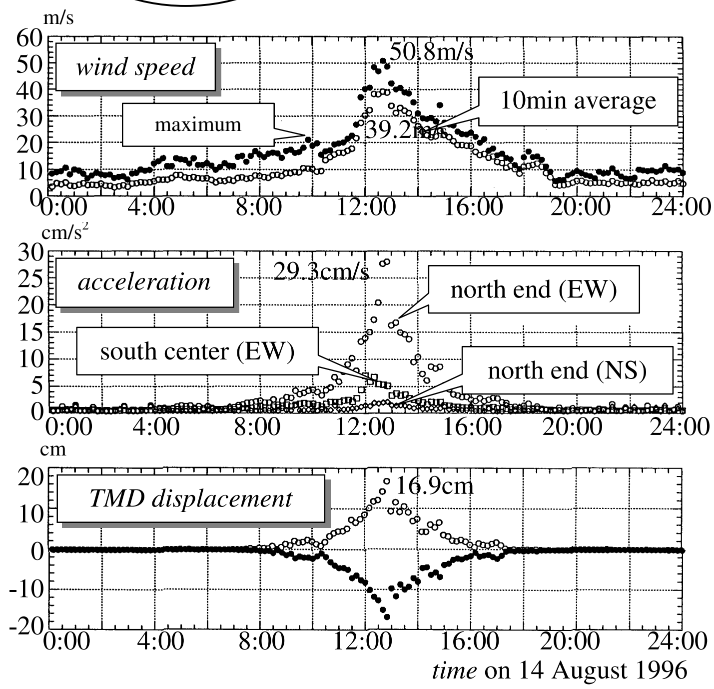


Figure 6: Strong wind and building response by typhoon 9612

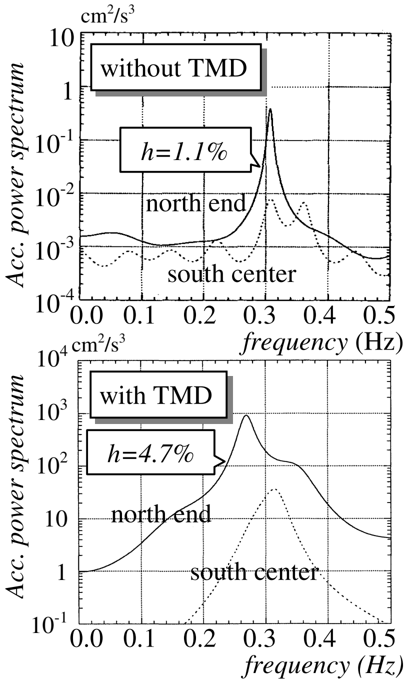


Figure 8: Effect of TMD

3.2 Earthquake record in Crystal Tower:

Crystal Tower was struck by a small earthquake on 24 September 1990. The peak accelerations in the NS direction observed in the tower were 7cm/s^2 at ground floor level and 10cm/s^2 at the top floor of the building. The behavior of the top floor and the TMD are simulated through the response analysis of a structure-pendulum-sloshing model in the NS direction excited by the ground floor acceleration record and the effect of the TMD is analytically examined. The damping of the structure is assumed to be 0.5% critical. The earthquake data were recorded during 95s. The responses after 95s are extrapolated by the simulation analysis.

The time histories, both observed and simulated, are compared in Figure 9. The peak displacement observed at the rooftop of the building and the relative displacement between the building and the TMD are 0.9cm and 1.9cm, respectively. A simulation analysis with the TMD shows a good agreement with the observed records and is reasonably assumed to be able to extrapolate the time histories in the last parts of the records. It is concluded from the simulation analysis that the TMD can damp the building's lateral motion quickly after earthquakes, which is particularly remarkable for high-rise buildings.

3.3 Earthquake record in Sea Hawk Hotel & Resort:

An earthquake also struck Sea Hawk Hotel & Resort on 19 October 1996. The epicenter was located 240 km southeast of Fukuoka as illustrated in Figure 10. The magnitude of the earthquake was 7.0. Figure 11 gives the observed accelerations at the ground level with maxima of 3.2 cm/s^2 in the EW direction and 5.5 cm/s^2 in the NS direction. The observed displacement responses were 2.3 cm of the tower at the north end on the rooftop and 5.6 cm of the TMD. The simulation response analysis was made in order to confirm the TMD effect during the earthquake. Figure 12 explains the simulation analysis model with TMD and Figure 13 compares the dominant periods and vibration modes between the models with and without the TMD. It should be noted that the first and the second modes coupled with torsion and translation in the model without the damper are de-coupled into two torsion modes and one translation mode by the damper.

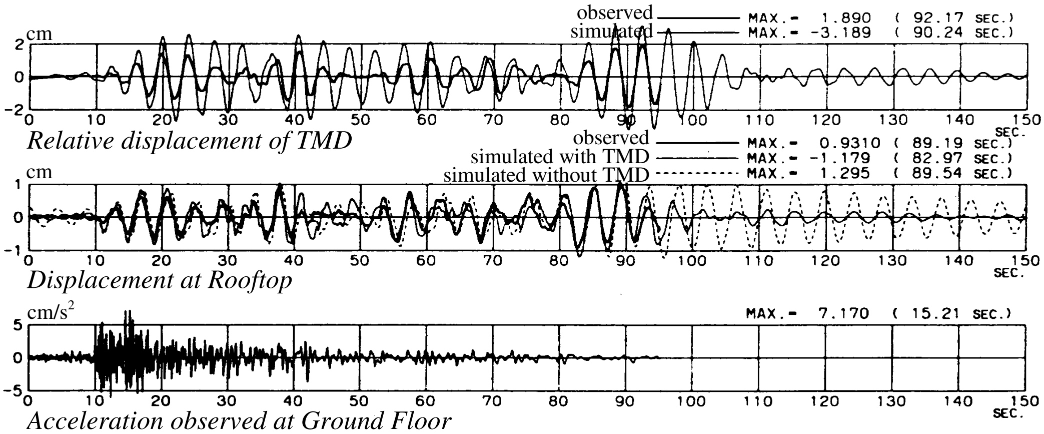


Figure 9: Simulation of earthquake response (24 September 1990) (Crystal Tower)

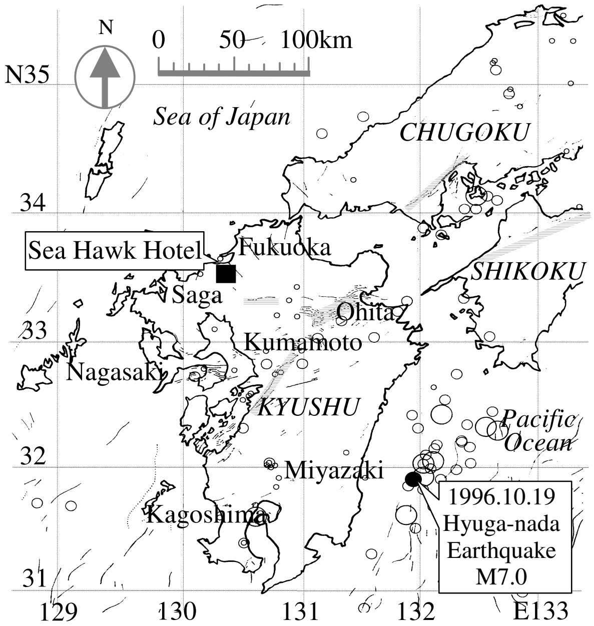


Figure 10: 19 Oct.1996 Hyuga-nada earthquake

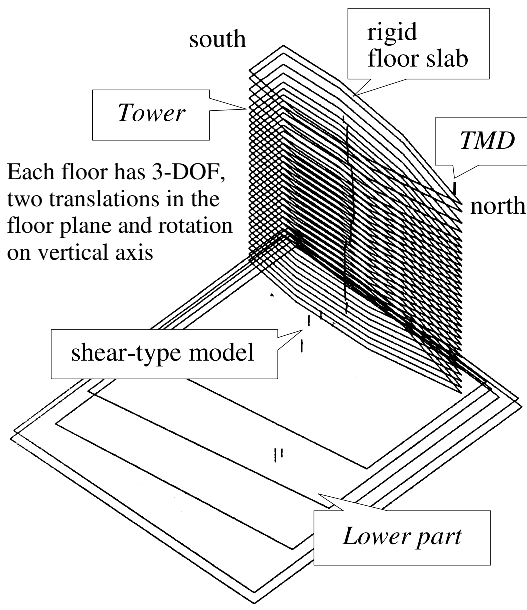


Figure 12: Simulation analysis model
(Sea Hawk Hotel & Resort)

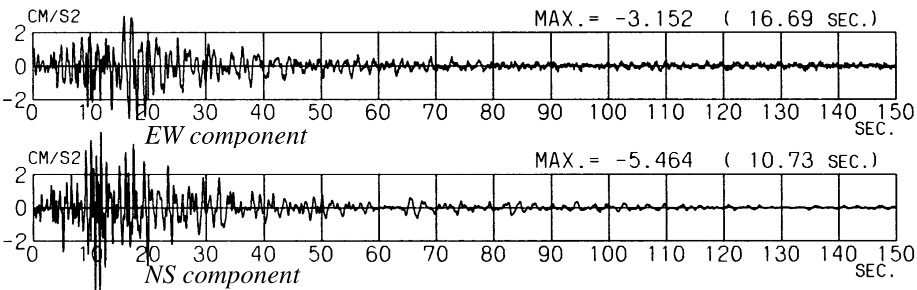
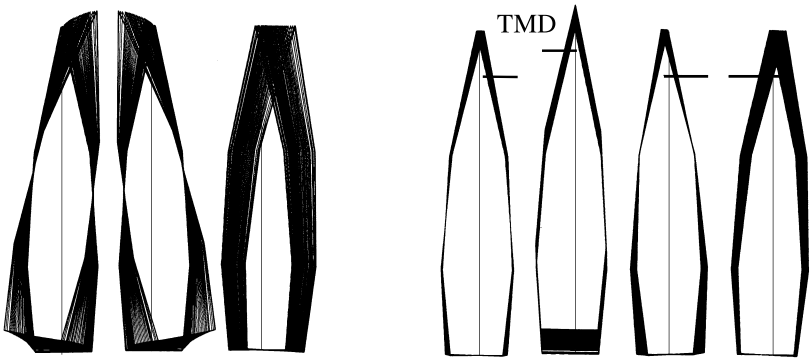


Figure 11: Earthquake records observed at ground level (Sea Hawk Hotel & Resort)



Without TMD

1st	2nd	3rd
0.300Hz	0.305Hz	0.345Hz
3.33sec	3.28sec	2.90sec

With TMD

1st	2nd	3rd	4th
0.279Hz	0.302Hz	0.318Hz	0.353Hz
3.59sec	3.31sec	3.14sec	2.83sec

Figure 13: Modes of simulation model with and without TMD (Sea Hawk Hotel & Resort)

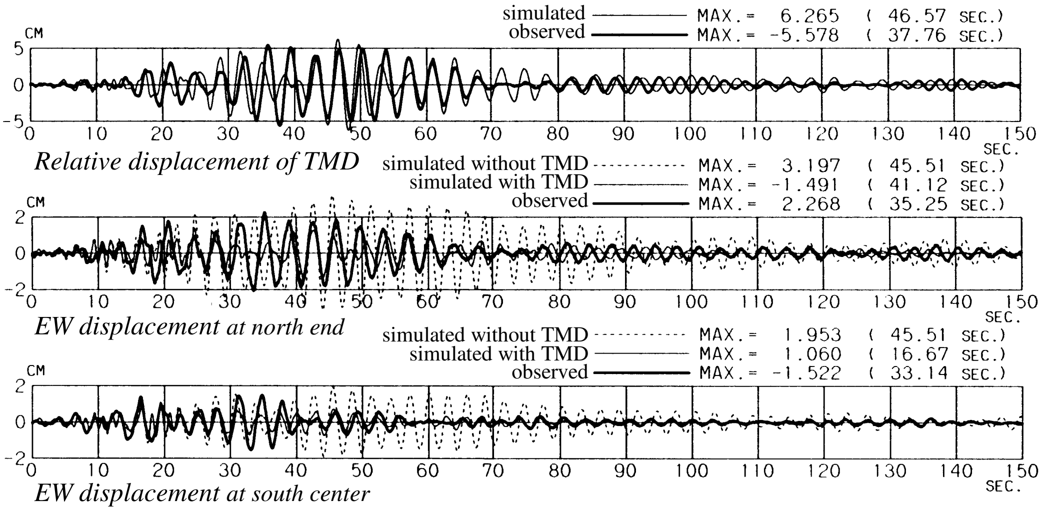
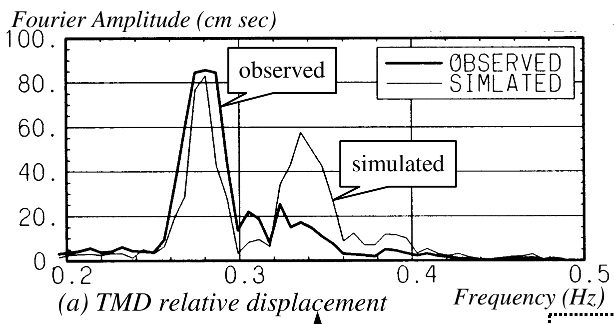
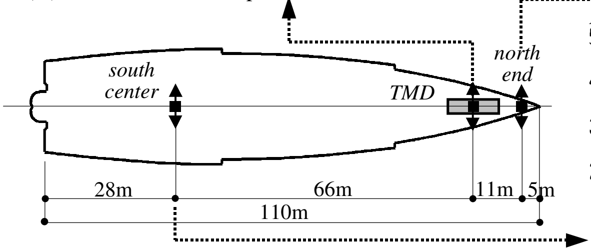


Figure 14: Simulation of earthquake response (19 October 1996) (Sea Hawk Hotel & Resort)





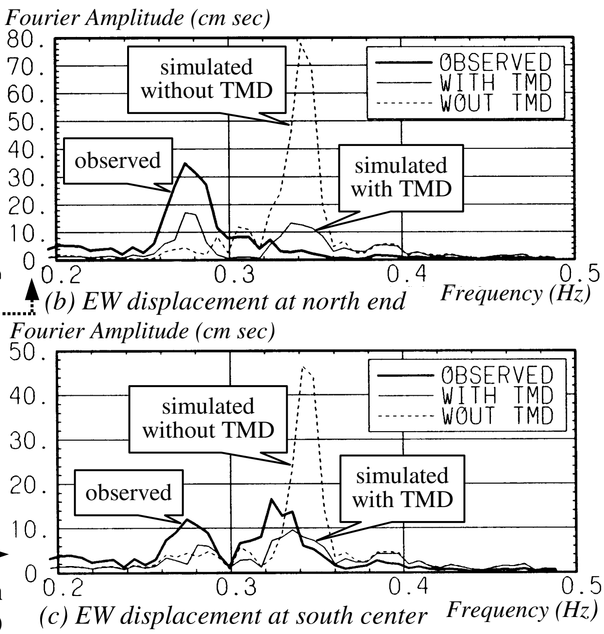


Figure 15: Comparison of Fourier Spectra between observation and simulation (Sea Hawk Hotel & Resort)

The models were excited by the EW and the NS accelerations observed at the ground level simultaneously. The time histories, observed and simulated with or without the damper, are compared in Figure 14. A simulation analysis with the TMD shows a good agreement with the observation including the beat motion in the latter part of histories due to close eigenvalues. The earthquake analysis confirms that against a class of relatively small earthquake motion the TMD can damp quickly the vibration of the tower after the main shock of the earthquake.

The displacement Fourier spectra are compared in Figure 15 between the observation and the simulation. In the model without the damper the EW translation mode of 0.3Hz dominates more than the torsion mode of 0.34Hz at both the north end and the center of the tower. In the model with the damper tuned to the torsional motion, however, the original translation mode of the building is decreased remarkably and two torsional translation mode of 0.28 and 0.32 Hz are noticed, which corresponds well to the observation.

4. CONCLUDING REMARKS

A tuned mass damper of pendulum type has been developed using mechanical equipment tanks at the building top floor as a moving mass of the damper and installed in tall buildings in Japan, two office buildings and one hotel building. The damper of this type needs no additional mass nor space because the building equipment such as the ice thermal tank or the elevated water tank are integrated into the damper, so it is very economical. In fact the damper cost are about 0.2% in Crystal Tower and 0.03 % in Sea Hawk Hotel & Resort of the construction cost of the whole building. The pendulum TMD using the equipment tanks is not a sloshing damper. Sloshing of the tank should be suppressed. The tanks have the correct dimensions for sloshing behavior not to be stimulated by the swinging of the TMD. When the sloshing frequency is kept higher than the twice of the pendulum frequency, the TMD fundamental will agree with the pendulum frequency and will be little affected by the practical variation of water volume in the tank.

Typhoon records observed in the buildings with the pendulum damper prove that the TMD increases the damping ratio of the building to critical from 1% to 4% or more and lessens the building vibration by 50%. The earthquake observation indicate that the damper cannot decrease the building responses during the main shock of the ground motion but can suppress the growth of the building's motion quickly after the main shock. The TMD for torsional vibration reduction divides the original coupled modes of torsional translations into torsion and translation and can improve the response behaviors.

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