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ENHANCEMENT OF BASE-ISOLATION BASED ON E-DEFENSE FULL-SCALE SHAKE TABLE EXPERIMENTS: DYNAMIC RESPONSE OF BASE-ISOLATED BUILDING UNDER IMPACT DUE TO POUNDING

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Abstract

In the recent years, occurrence of large displacement of base-isolation system due to long-duration, long-period ground motions are concerned. Especially, after the 2011 off the Pacific coast of Tohoku Earthquake, a lot of seismologists predicted strong subduction motions in Tokai, Tonankai and Nankai area including strong long period components.

The large displacement of base-isolation system may cause rapture of the isolation devices or pounding of the building to the retaining walls at the base. Large impact accelerations due to pounding may strongly affect to the functionality of building.

To evaluate impact accelerations due to pounding, full-scale shake table experiments of base-isolated building were conducted. The specimen was four-story RC building with eccentricity supported by two rubber bearings and two sliding bearings. Two types of energy dissipation devises were used; the steel U-shaped dampers and oil dampers.

In the experiment, three pounding conditions were assumed; 1) pounding to 150mm-thick rubber blocks attached at the top of retaining walls to mitigate shock with clearance of 400mm, 2) ponding to 150mm-thick rubber blocks with clearance of 300mm and 3) directly pounding to concrete with clearance of 400mm.

This paper represents floor response due to pounding and discusses about the accuracy of analysis.

Based on the experiment, it was found that floor acceleration larger than 30 m/s^2 was observed when superstructure pounded to ridged retaining walls with thickness of 400mm while there was less significant damage to structural members and furniture. It was also found that the 150mm-thick rubber blocks attached at the top of retaining wall can mitigate floor acceleration and displacement pounded retaining walls, however, furniture inside specimen still fell down or slipped.

Keywords: Base-isolation, Pounding, Retaining wall, Full-scale shake table experiment, E-Defense

1. Introduction

In the recent years, occurrence of large displacement of base-isolation system due to long-duration, long-period ground motions are concerned. Especially, after the 2011 off the Pacific coast of Tohoku Earthquake, a lot of seismologists predicted strong subduction motions in Tokai, Tonankai and Nankai area including strong long period components.

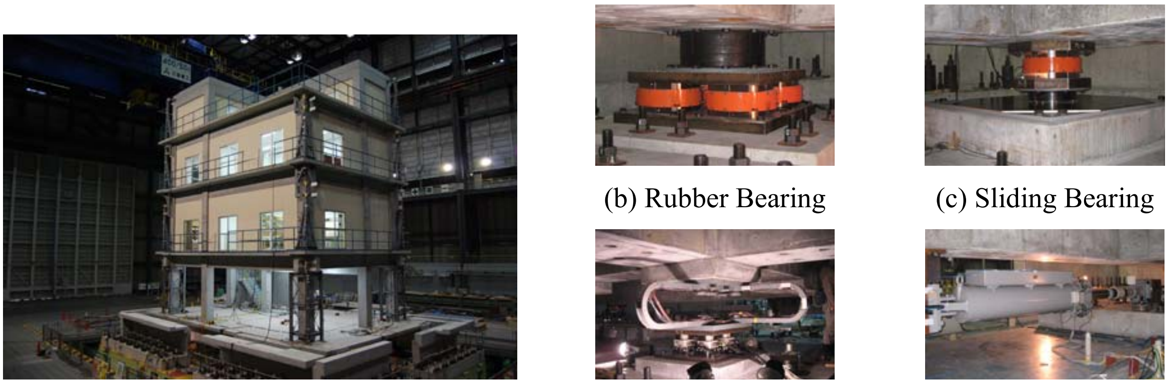
The large displacement of base-isolation system may cause rapture of the isolation devices or pounding of the building to the retaining walls at the base. Large impact accelerations due to pounding may strongly affect to the functionality of building.

Several researchers studied about pounding of base-isolated building based on analysis and small-scale experiments [for example 1 and 2]. On the other hand, there a few studies on evaluation of pounding based on real-scale experiment. Miwada et al. conducted free-vibration pounding experiment of base-isolated building to be demolished [3]. Based on experimental results, they obtained increment of inter-story displacement and floor acceleration and restoring force characteristics of retaining walls including soil behind under collision response. They also clarified that the behavior of superstructure during collision can be well simulated using the model with sway springs for the retaining walls, which obtained from the above experiment.

As described the recent studies shown in above, the pounding behavior of superstructure was evaluated based on free-vibration experiment. However, application of these facts to real structures under real earthquake is not verified. Thus, full-scale shake table experiments of base-isolated building were conducted to evaluate effect of impact accelerations due to pounding on structural members and nonstructural components. This paper presents results of experiments.

2. Specimen, Setup and Experimental Plan

2.1 Full-scale Base-Isolated Building Specimen, Isolation Devices and Retaining Walls



(b) Rubber Bearing (c) Sliding Bearing

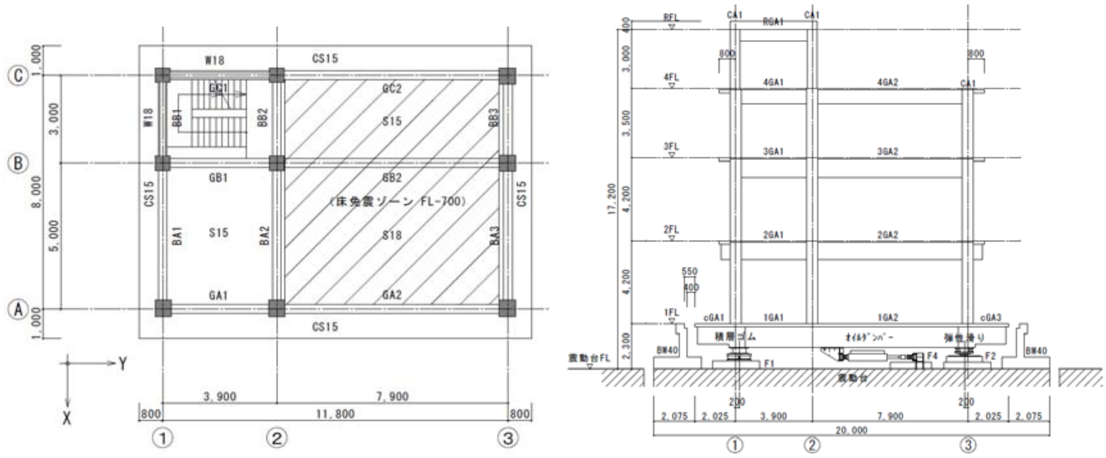
(a) Overall View (d) U-Shaped Steel Damper (e) Oil Damper

Photo 1 Full-scale Base-isolated Building Specimen

Photo 1 and Fig. 1 show full-scale base-isolated building specimen and retaining walls around specimen. As shown in Fig. 1, X and Y directions are defined as the direction of narrow and wide side, respectively, in this paper. The specimen was designed as base-isolated building which widely used in Japan. The superstructure was four story RC moment frame building with multi-story seismic shear wall at south-east side and 4th floor was setback to south-east side. Therefore, center of gravity and stiffness was off-center to south-east side.

Table 1 shows summary of members. The columns had square section with width of 550mm at 1st to 3rd floors and 500mm at 4th floor. Longitudinal bars and ties of the columns were deformed bars with diameters of 25mm and 10mm, respectively. The beams had rectangular section with width of 300mm for all beams except base and height of 900mm, 700mm and 600mm for beams located at 2nd to 3rd floors, 4th floor and roof levels, respectively. Longitudinal bars of the beams were deformed bars with diameters of 25mm and 22mm and ties of the beams were deformed bars with a diameter of 10mm. The multi-story seismic shear walls had a thickness of

180mm at 1st-3rd floors and 150mm at 4th floor and they had deformed bars with a diameter of 10mm in both horizontal and vertical directions. Total weight of superstructure was about 687 tons.



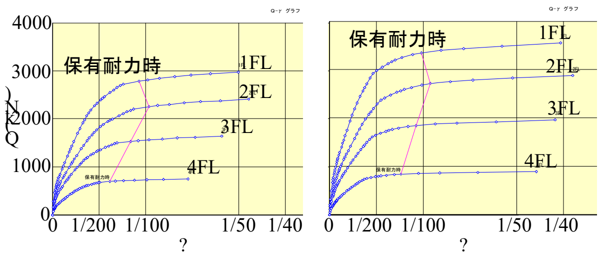
(a) Plan View (2nd floor) (b) Sectional View (Section A)

Fig. 1 Superstructure

Table 1 Section of Members

Member	Size (mm)
Column	550x550, 500x500
Shear Wall	t=180, 150
Beam	300x900, 300x800,300x700
Base Beam	1300×1200
Slub	150
Retaining Wall	T=200,400

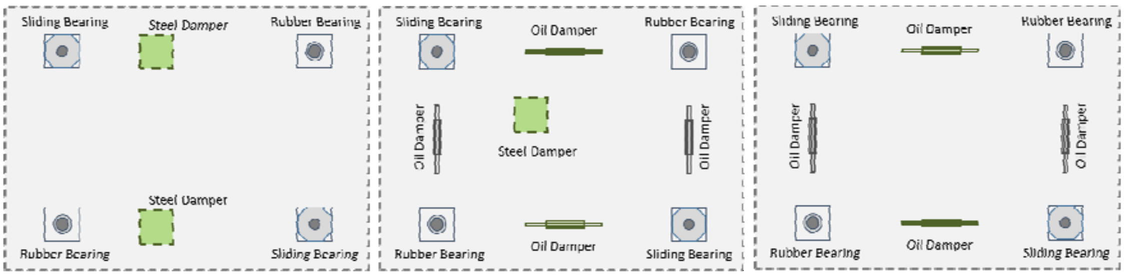
Fig. 2 shows result of pushover analysis under Ai distribution. Lateral strength defined as the restoring force when inter-story drift angle reached 1/100 in any floors is also shown in Fig. 2. As shown in Fig. 2, Base-shear coefficient defined as lateral strength divided by total weight of structures in above floors was 0.66 and 0.82 in in X and Y directions, respectively. Based on the results shown in Fig. 2, natural periods of superstructures with base-fixed were the range of 0.43 to 0.44 sec.



(a) X (b) Y

Fig. 2 Result of Pushover Analysis using Ai Distribution

Fig.3 shows three different configuration of isolation devices used in the experiment. Table 3 shows detail specification of isolation devices. In all cases, same bearing setup was used; two natural rubber bearings with a diameter of 650mm and two sliding bearings having a low friction coefficient with the range of 0.014 to 0.018 were installed at the underneath of the four corner columns of superstructure as shown in Fig. 1(c). On the other hand, damper setup was different in three cases. In Case 1, two steel dampers installed at the edge center of wide side. In Case 2, combination of one steel damper and four oil dampers were installed. In Case3, four oil dampers were installed in four edges. As shown in Table 2, oil dampers were designed as dampers with a function of variable damping force due to electro-magnetic valves controlled by electric circuit for future study on semi-active control of real structures. In this experiment, oil dampers were used as passive dampers so that damping coefficient of oil dampers were set to 125 kN/(m/s) and 250 kN/(m/s) in Cases 2 and 3, respectively.



Case 1 Case 2 Case 3

Fig. 3 Setup of Isolation Devices

Table 2 Isolation Devices

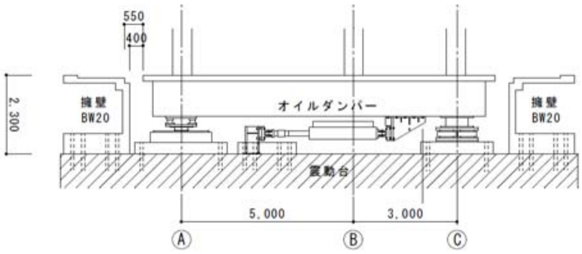
(a) Bearings

Rubber Bearing (Natural Rubber)		Type		NL065G4
		Outer Diamter	mm	650
		Rubber Thickness	mm	162.8
		Horizontal Stiffness	kN/m	800
		Vertical Stiffness	kN/m	1,960,000
Low Friction Sliding Bearing with Rubber Bearing	Rubber Bearing	Type		SP040G4
		Outer Diamter	mm	400
		Rubber Thickness	mm	41.6
		Diamter of Sliding Plate	mm	360
		Horizontal Stiffness	kN/m	1,570
		Vertical Stiffness	kN/m	2,670,000
	Sliding Plate	Type		QP16231
		Plate Width	mm	1,600
		Friction Coefficient		0.014～0.018

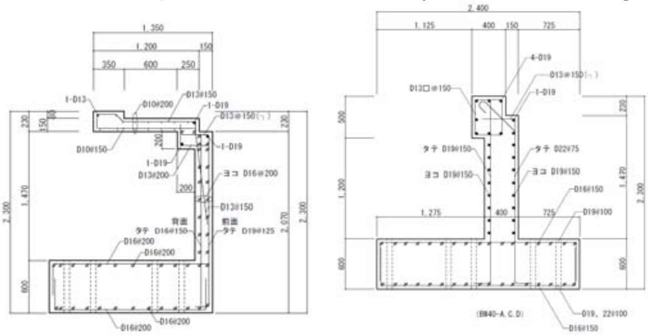
(b) Dampers

U-Shaped Steel Damper	Type		NSUD50x2
	Yield Strength	kN	116
	Initial Stiffness	kN/m	4,160
	Post Yield Stiffness	kN/m	72
Variable Oil Damper	Type		BM260
	Number of Steps of Variable Damping Force		5
	Damping Coefficient C	kN/(m/s)	125(= C_L) 250(= C_H)
	Maximum Velocity	m/s	1.6
	Maximum Damping Force	kN	400

Equivalent natural periods of base-isolated building specimen in maximum displacement of 300mm were 3.2 sec, 3.5 sec and 3.9 sec in Cases 1, 2 and 3, respectively. Equivalent damping coefficients were 0.21, 0.25 and 0.29, respectively.



(a) Sectional View (Section 3, Isolation Layer with Retaining Walls)



(b) Retaining Wall BW20 (c) Retaining Wall BW40

Fig. 4 Full-scale Base-isolated Building Specimen

Table 3 Retaining Walls

Name	Thickness (mm)	Rebars at Tension Side	Retaining Wall Strength Ratio	
			Overall Pounding	Partial Pounding
BW20	200	D19@125	0.12	0.04
BW40	400	D22@ 75	0.56	0.21

Fig. 4 and Table 3 shows detail of retaining walls. Retaining wall strength ratio defined as the ratio between strength of retaining wall and weight of superstructure was also shown in Table 3. Retaining wall strength ratio for overall pounding is evaluated from retaining wall strength resisting whole walls with width of 5m assuming pounding the overall edge of superstructures to retaining walls. On the other hand, retaining wall strength ratio for partial pounding is evaluated from retaining wall strength resisting summated width resulting from assuming partial pounding width of 0.5m at the top of walls and double of 1.6m width under assumption of 45 degrees force transferring to the base. As shown in Table 3, in this experiment, two different retaining walls were installed; 1) 200mm thick RC retaining walls BW20 at the edge of wide side and 2) 400mm BW40 at the edge of narrow side. BW20 was designed as a 200mm thickness standard retaining wall for base-isolated building with 2-3m depth shallow pit while BW40 was designed as 400mm thickness ridged retaining wall for base-isolated building with 7m depth deep pit for basement floors. Both BW20 and BW40 had notches at the top of walls to set 150mm thick RC blocks or 150mm thick rubber blocks for control of clearance between superstructure and retaining walls and evaluation of effect of different characteristics of pounding parts. In this experiment, clearance between superstructure and retaining walls were set in three different values of 550mm, 400mm and 300mm.

Several furniture was installed inside specimen as shown in Table 4, to evaluate the functionability after strong motions.

Table 4 Function of Rooms inside Specimen

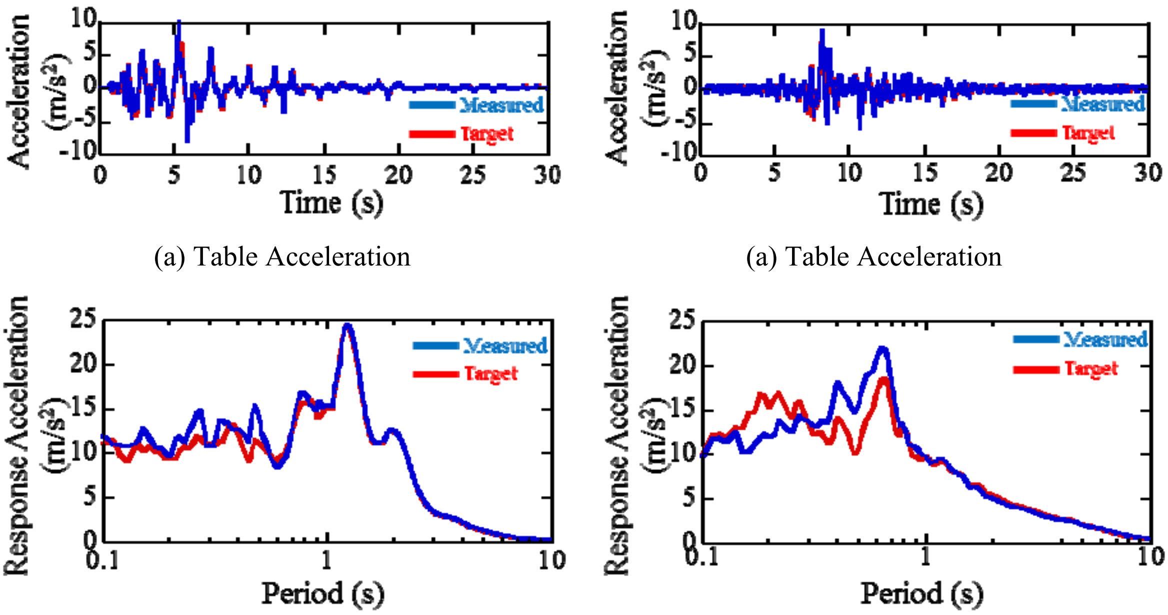
4F	School classroom and museum
3F	Medical rooms and plant control room
2F	Laboratory, server room and living space
1F	Store room, shutters and expansion joints

2.2 Imposed Motions

Table 5 shows imposed motions used in this experiment and Fig. 5 shows time history and response spectrum of two examples of imposed motions. In this experiment, two near-fault motions; 1) Takatori record observed at JR Takatori station during 1995 Kobe earthquake and 2) Tennoji motion which is one of artificial motions assumed to observed at Osaka during near-fault earthquake with epicenter at Uemachi fault in Osaka area [4], and three subduction motions; 3) Furukawa record observed at K-NET Furukawa station during 2011 Tohoku earthquake, 4) Sannomaru motion which is an artificial motion assumed to observed at Nagoya during assumed Tokai and Tonankai earthquake [5] and 5) Osaka-fucho motion which is artificial motion observed at Osaka Prefecture Government hall during subduction earthquake with coupled raptures at Tokai, Tonankai, Nankai and off the Nankai Trough areas, were used. Because of the limitation of papers, result of two near-fault motions; Takatori record and Tennoji motion were described in this paper, as shown in Fig. 5.

Table 5 List of Imposed Motions

Name	Type	Earthquake	Peak Acceleration (m/s^2)		
			X	Y	Z
Takatori record	Near-fault ground motions	1995 Kobe earthquake	6.39	6.64	2.90
Takatori record (Rotate 45 degrees to maximize response to BW40)			5.95	7.64	2.90
Tennoji motion (Rotate 45 degrees to maximize response to BW20)		Assumed Uemachi fault earthquake	9.47	5.63	5.67
Furukawa record	Subduction motions	2011 Tohoku earthquake	4.46	5.65	2.36
Sannomaru motion		Assumed Tokai and Tonankai earthquake	1.66	1.86	1.16
Osaka-fucho motion		Assumed Tokai, Tonankai, Nankai earthquake	1.39	0.73	0.32



(a) Table Acceleration (a) Table Acceleration

(b) Response Acceleration (b) Response Acceleration

(1) Takatori Record (90%, Y direction) (2) Tennoji Motion (72%, X direction)

Fig. 5 Imposed Motions

Based on the result of preliminary simulations, intensities of imposed motions were scaled down or up to appropriate level from original motions. For example, intensity of Takatori record was imposed 90% maximum of original Takatori record and that of Tennoji motion was imposed 72% maximum of original Tennoji motion.

2.3 Instrumentation Plan

Accelerometers were set in the top of the table, floor slabs to measure table and floor accelerations. Wire pods were set between the table and the base- beams to measure displacement of the base beam. Laser displacement transducers were set every floors to measure interstory displacement. Displacements and accelerations were also measured at the top of retaining walls. Longitudinal bars in several columns, beams and retaining walls had strain gauges.

3. Results

3.1 Response without Pounding

Fig. 6 shows ratio of RMS (root mean square) values of floor acceleration at 1st floor and table acceleration varying in peak table acceleration under all ground motion excitations except experiments pounding occurred. As shown in Fig. 6, in the range of large table acceleration larger than 5 m/s^2, floor acceleration decreased about a half of table acceleration and base-isolation system worked well in all three cases. On the other hand, floor acceleration mitigate more in Case 3, using oil dampers as damping devices, than Cases 1 and 2, using steel dampers because damping force of steel dampers are almost constant if isolation displacement exceeds yield displacement of steel dampers, and it may be large enough comparing with inertia force due to ground motions. In the range of table acceleration smaller than 2 m/s^2, floor acceleration amplified from table acceleration in Cases 1 and 2, because imposed motions for their experiment were Osaka-fucho motion, having small peak table acceleration and including large long period components which excited resonance vibration to structures with natural period of 4-5sec.

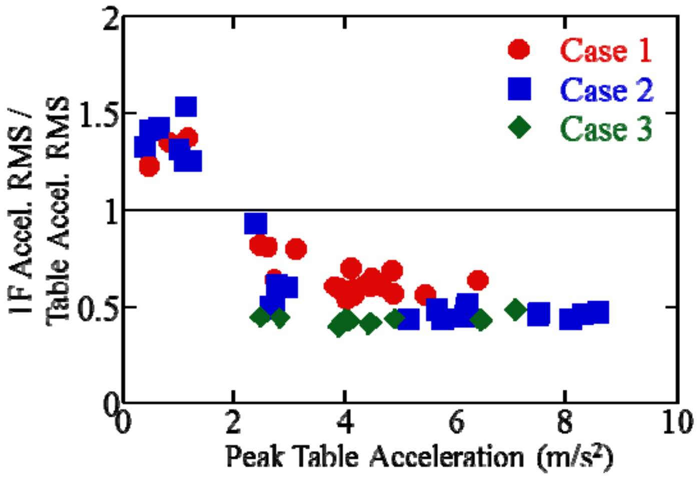


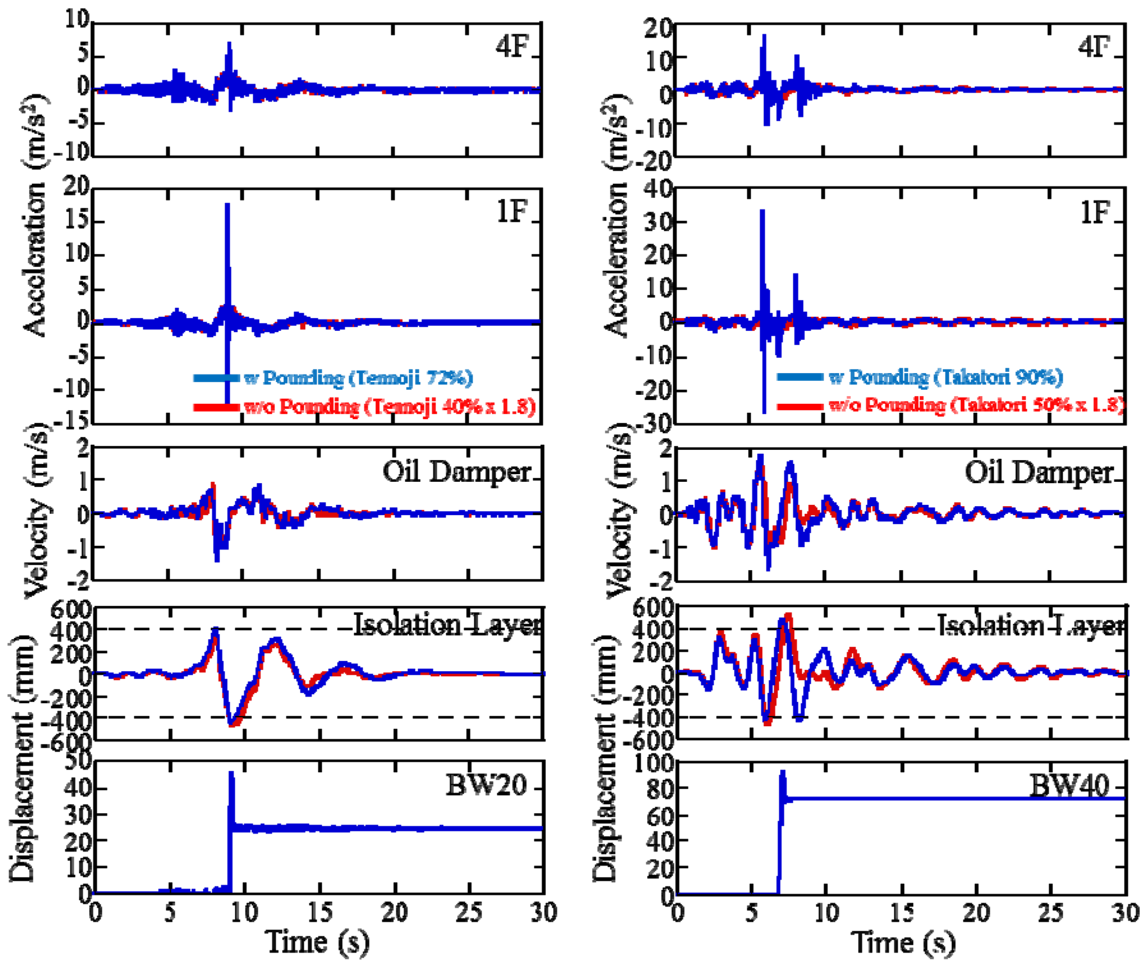
Fig. 6 Decrement of Floor Acceleration by Base-Isolation

3.2 Damage and Response due to Soft Pounding to BW20

Photo 2 shows damage after pounding to BW20 under Tennoji 72% excitation. Note that the configuration of isolation devices was case 3 with clearance of 400 mm in this experiment. It should be also important noted that BW20 is thinner and softer retaining walls than BW40. Thus, this pounding may be mild impact to superstructure and furniture inside it. As shown in Photo 2, the major damage inside specimen was movement of unfixed objects while there was no structural damage to superstructure. The pounded retaining walls, BW20, was failed in flexure at the base.

Fig. 4 shows floor accelerations, velocity of oil damper, displacement of isolation layer, response displacement at the top of BW20 under Tennoji 72% excitation. Response without pounding under Tennoji 40% excitation is also shown in Fig. 4(a) for comparison. Noted that intensity of imposed motion was different between response with and without pounding so that response without pounding is amplified at 1.8 times. Response under Takatori 90% shown in Fig. 4(b) will be described later. Large response acceleration at 1st floor, 17.6 m/s^2, can be observed and it was more than 7 times larger than that without pounding.

Photo 2 Damage after Pounding to BW20 under Tennoji 72% Excitation (Case 3)



(a) Tennoji 72% with Pounding to BW20 (b) Takatori 90% with Pounding to BW40

Fig. 4 Response of Superstructure, Isolation Devices and Retaining Walls (Case 3)

In this paper, instance of pounding is defined as the time when sudden displacement increment of pounded retaining walls, hereinafter. Based on Fig. 4(a), instance of pounding was observed at 9.00sec and velocity of oil damper at this time, which can be defined as pounding velocity was 0.60 m/s.

Peak and residual displacements of pounded retaining walls, BW20, were 45 mm and 25 mm, respectively. It is noted that yield and ultimate displacements of BW20 is 10 mm and 19 mm, respectively. Thus, state of BW20 exceeds ultimate state and BW20 may lost its function.

3.3 Damage and Response due to Hard Pounding to BW40

Photo 3 shows damage after pounding to BW40 under Takatori 90% excitation. Note that the configuration of isolation devices was also case 3, same as the above discussion, in this experiment. It should be also important noted that BW40 is thicker and more rigid retaining walls than BW40. Thus, this pounding may be severe impact to superstructure and furniture inside it. Major damage inside specimen was movement of heavy furniture with peeling off of floor panels. The superstructure pounded to east BW20 twice and west BW20 once The pounded retaining walls, BW40, completely collapse in shear as shown in Photo 3. More severe damage observed at west BW40. On the other hand, there are few structural damage to superstructure.

Photo 3 Damage after Pounding to BW40 under Takatori 90% Excitation (Case 3)

As shown in Fig. 4(b), floor accelartion at 1st floor exceeded 30 m/s^2 and transfered to top of specimen. Floor acceleration at 4th floor was also close to 20 m/s^2. However, structural damage was less as described above even though huge floor acceleration was observed. Based on Fig. 4(b), instances of pounding were 5.80 sec, 6.78 sec and 8.07 sec and pounding velocities were 0.73 m/s, 0.91 m/s and 0.38 m/s, respecively. Peak and residual dispalcemnts of pounded retaining walls, BW40, were 92 mm and 72 mm, respectively. Noted that yeild displacement of BW40 assuming failed in flexure is 6.6 mm. Thus, the peak displacement of BW40 was 14 times of yield displacement.

3.4 Damage Mitigation by Rubber Blocks

Photo 4 shows damage after pounding to BW40 with rubber blocks. Note that the configuration of isolation devices was case 2, different configuration with the case described above, with clearance of 300 mm in this experiment. In this experiment, the superstructure pounded to east BW40 twice and west BW40 once. As shown in Photo 4, several shelves fell down. This fact means rubber blocks cannot mitigate the damage of furniture inside building. However, damage to the pounded retaining walls, BW40, had only crack. Thus, rubber blocks, not retaining walls itself, might absorb kinetic energy of superstructure.

Photo 4 Damage after Pounding to BW40 with Rubber Blocks under Takatori 65% Excitation (Case 2)

Fig. 5 shows floor accelerations, velocity of oil damper, displacement of isolation layer, response displacement at the top of BW40 under Takatori 65% excitation. Based on Fig. 5, instances of pounding were 5.90 sec, 6.91 sec and 7.96 sec, and pounding velocities were 0.82 m/s, 0.69 m/s and 1.01 m/s, respectively. Thus, more severe pounding occurred than pounding described in the above section. However, floor accelerations were smaller than that pounding to BW40 without rubber blocks, described above. Therefore, rubber blocks relatively mitigated impact acceleration due to pounding, however absolute values of floor accelerations still large (close to 10 m/s^2 or more) so that damage to furniture was observed. On the other hand, response displacement of BW40 was only 6 mm, which is close to yield displacement, significantly decreased.

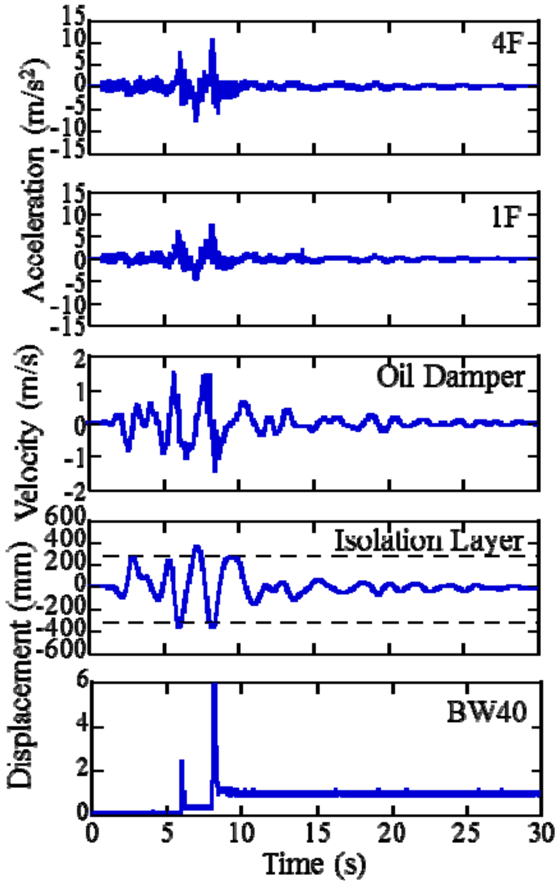


Fig. 5 Response of Superstructure, Isolation Devices and Retaining Walls under Takatori 65% Excitation with Pounding to BW40 with Rubber Blocks (Case 2)

4. Summary

To evaluate effect of pounding on damage of base-isolated buildings, shake table experiment using full-scale base-isolated building specimen with realistic retaining walls was conducted. Based on the experiment, it was found that floor acceleration larger than 30 m/s^2 was observed when superstructure pounded to ridged retaining walls with thickness of 400mm while there was less significant damage to structural members and major damage to furniture was only movement of unfixed furniture or falling down.

Installation of rubber blocks between superstructure and retaining walls can be mitigate floor acceleration due to pounding and displacement of pounded retaining walls. However furniture inside superstructure still fell down or slipped by impact acceleration due to pounding.

5. Acknowledgements

The pounding shake table experiment on full-scale base-isolated building was conducted based on the extensive support of Isolation and Vibration Control Experimental Research Committee (Chief Professor Satoshi Fujita (Tokyo Denki University), Associate Professor Taichiro Okazaki (Hokkaido University), Associate Professor Mamoru Shimazaki (Tokyo Metropolitan College of Industrial Technology), Professor Mineo Takayama (Fukuoka University), Professor Hidekazu Nishimura (Keio University) and Professor Hideo Fujitani (Kobe University)) for experimental plan and design of base-isolated specimen with retaining walls.

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