# Experimental verification of passively variable oil damper applied to seismically isolated houses for response reduction

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**SUMMARY:**
In this study, a passively controlled i.e. variable oil damper with velocity is applied to seismically isolated houses to reduce the response against earthquake motions with high velocity amplitude and long period component. The viscous characteristics are changed through controlling flow of fluid mechanically. Through the numerical calculation, appropriate characteristics of the damper are investigated under a lot of observed and simulated earthquake motions. The variable oil damper which is manufactured is tested. By the dynamic test, it is demonstrated that the damper has similar characteristics to the design ones and shows enough performance for practical application. Through the shaking table test using a seismically isolated model, effects of the damper on displacement and acceleration response of the model are confirmed. The displacement response is reduced and is able to be kept less the design limitation of isolators.

*Keywords: Seismic isolation, Variable oil damper, Dynamic test, Severe earthquake motion, Response reduction*

## 1. INTRODUCTION

Recently earthquake ground motions whose maximum velocities exceed 100 cm/s have been observed. When the earthquake motions with large amplitude and/or long period component act on seismically isolated buildings, displacement responses of isolated layers will be large and sometimes exceed the limitation of isolators. In case of family houses, clearances at surroundings or isolated layers are not enough to the large displacement response. As a result, a collision of isolated layer or damage of isolator will probably occur during these earthquakes. Countermeasures for response reduction of isolated layer with energy absorption devices are necessary, to keep safety during a main shock and aftershocks and sustainability of residence after earthquakes. Adding energy absorption devices, maximum displacement responses of isolators need to remain less than the design limitation.

As controlled oil dampers, the researches and applications of a magneto-rheological (MR) fluid damper (Yoshioka et. al., 2002; Fujitani et. al., 2005) and oil damper systems (Kurino, 2002) are conducted. The MR damper and the systems are controlled semi-actively. Recently the oil damper system with passive control (Kurino, 2004 & 2006) to reduce the response against earthquakes and strong winds has been developed.

In this study, a passively controlled i.e. variable oil damper with velocity is applied to a seismically isolated system to reduce the response against earthquake motions with high velocity amplitude and/or long period component. The viscous characteristics are changed mechanically. The mechanism provides that the low viscous damping force will be kept under the earthquake motions whose velocities are not so high. When the relative velocity of isolated layer will exceed a certain value, the damping force will be large at that time. Appropriate characteristics of variable oil damper for the demand performance of the systems are confirmed, through numerical calculation. The manufactured damper is tested by the high-velocity type actuator. Through a shaking table test, effects of the damper on the displacement of isolated layer and acceleration of superstructure are investigated.

## 2. EARTHQUAKE MOTION

Predominant periods of isolated houses are designed to be about 3 to 4 seconds. Earthquake motions in Japan which have a large amount of velocity response in these periods are observed (JMA; NIED-K-NET; Nakamura *et al.*, 1996; Osaka Gas, 1995). Recently earthquake motions which have a long period component are proposed (AIJ, 2007). These earthquake motions will occur in large-scaled alluvial plains, that is., Kanto and Osaka sedimentary basins due to a huge earthquake along the shore of the Pacific Ocean side. A list of simulated and observed earthquake motions is presented in Table 1.1. And pseudo velocity response spectra of these motions are drawn in Fig. 1.1. The observed earthquake motions have large velocity response spectra with 1 to 3 seconds in period.

**Table 1.1.** A List of Earthquake Motions

| | Name of earthquake & place | Name of earthquake wave | A ($cm/s^2$) | V (cm/s) | D (cm) | Duration time (s) |
|---|---|---|---|---|---|---|
| Simulated Motions | Kanto EQ, Tokyo | KAN-SAT-TOK-NS | 244 | 24 | 16.2 | 77.5 |
| | Kanto EQ, Yokohama | KAN-SAT-YKL-NS | 499 | 34 | 17.9 | 24.1 |
| | Tokai & Tonankai EQ, Nagoya, San-nomaru | TOKTON-CHU-SAN-EW | 186 | 51 | 20.4 | 119.9 |
| | Ditto, Nagoya station | TOKTON-AIC-NST-EW | 117 | 27 | 9.8 | 80.6 |
| | Ditto, Suijoh branch | TOKTON-AIC-SJB-EW | 187 | 50 | 19.1 | 85.6 |
| Observed Motions | 1995 hyogoken-nanbu EQ, JR Takatori | Takatori-NS | 642 | 131 | 46.9 | 11.3 |
| | Ditto, Osaka Gas, Fukiai | Fukiai-NS | 802 | 124 | 45.6 | 6.8 |
| | 2003 Off Tokachi EQ, K-NET, Tomakomai | Tomakomai-HKD129-EW | 73 | 35 | 29.0 | 89.5 |
| | 2004 Mid Niigata pref. EQ, JMA, Kawaguchi | Kawaguchi-EW | 1676 | 148 | 42.3 | 26.5 |
| | 2007 Niigata Chuetsu- oki EQ, K-NET, Kashiwazaki | Kashiwazaki-NIG018-NS | 667 | 109 | 55.0 | 6.6 |

A: Max. Acceleration, V: Max. Velocity and D: Max. Displacement

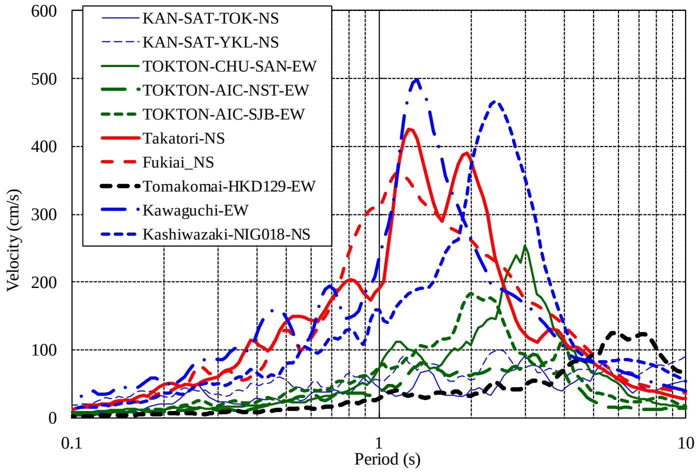



**Figure 1.1.** Pseudo velocity response spectra (damping factor = 5%)

## 3. RESPONSE OF SEISMICALLY ISOLATED HOUSE

### 3.1. Modelling of seismically isolated house

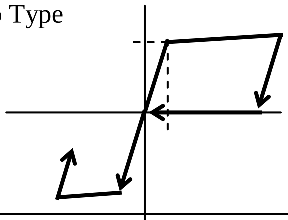
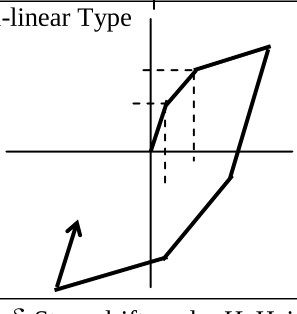
The seismically isolated house model has three degrees of freedom. The house is two-story superstructure with 2,700 mm in story height. The lowest mass is corresponding to that in a 1st floor level. The lowest story is an isolated layer. The mass ratios of the overall system along the height are 1.0, 1.0 and 0.6. Two types of seismically isolated models, rolling and sliding types are selected. These are used in the isolation systems of practical family houses in Japan. Characteristics of combination of isolators are summarized in Table 3.1. The rolling type is composed of a roller with coefficient of friction of 0.005, a restoring device whose natural period is 3 s and a viscous damper of 25% in damping factor. The sliding type is composed of a slider with coefficient of friction of 0.05 and restoring device whose natural period is 4 s.

**Table 3.1.** Characteristics of isolated layer

| System | Friction Coefficient | Period with Second Stiffness of Isolator | Viscous Damping Factor | Model Name |
|---|---|---|---|---|
| Rolling | 0.005 | $T_t$=3s | $h_v$=25% (Proportional to Stiffness at Period of $T_t$) | R-hv25 |
| Sliding | 0.05 | $T_t$=4s | $h_v$=0% | S-hv00 |

Relationships between story shear force ($Q$) and story drift ($\delta$) in the family house of two stories and characteristic values are summarized in Table 3.2. The shear force is expressed to non-dimensional shear force ($C$), dividing by total weight of higher part than the story. One of the superstructure models is a slip type which is a representative of steel structures with braces, and the other is a tri-linear type which is a representative of steel frames. The stiffness of non-structural members is not included in the characteristic values. The damping factors are assumed to be 5 %, and the damping force is set to be proportional to stiffness of stories.

**Table 3.2.** Characteristics of superstructure

| Kind of Model | Characteristics of $C$ and $\delta$ Curve |
|---|---|
| 1) Slip Type  | Stiffness :Initial Stiffness: $k_1$<br>Second Stiffness : $k_2 = 0.05k_1$<br>Yield Point: 1st Story : $\delta_1$=$H$/120, $C_1$=0.56<br>2nd Story: $\delta_1$=$H$/120, $C_1$=0.8<br>Damping Factor: $h$ =0.05<br>(Proportional to Initial Stiffness) |
| 2) Tri-linear Type  | Stiffness :Initial Stiffness: $k_1$, Second Stiffness : $k_2 = 0.4k_1$,<br>Third Stiffness : $k_3 = 0.05k_1$<br>1st Yielding Point:1st Story : $\delta_1$=$H$/200, $C_1$=0.2<br>2nd Story: $\delta_1$=$H$/200, $C_1$=0.3<br>2nd Yielding Point:1st Story : $\delta_2$=$H$/75, $C_2$=0.333<br>2nd Story: $\delta_2$=$H$/75, $C_2$=0.5<br>Damping Factor: $h$ =0.05<br>(Proportional to Initial Stiffness) |
| Note; $\delta$: Story drift angle, $H$: Height of story, $C$: Ratio of shear force to weight | |

### 3.2. Response of seismically isolated house

The displacement and velocity responses for seismically isolated houses are shown in Fig. 3.1. The response against simulated earthquake motions is not so large. In case that the maximum peak velocity of observed earthquake motion is larger than 100cm/s, the maximum displacement responses exceed 50cm and some responses of maximum velocity are about 200cm/s.

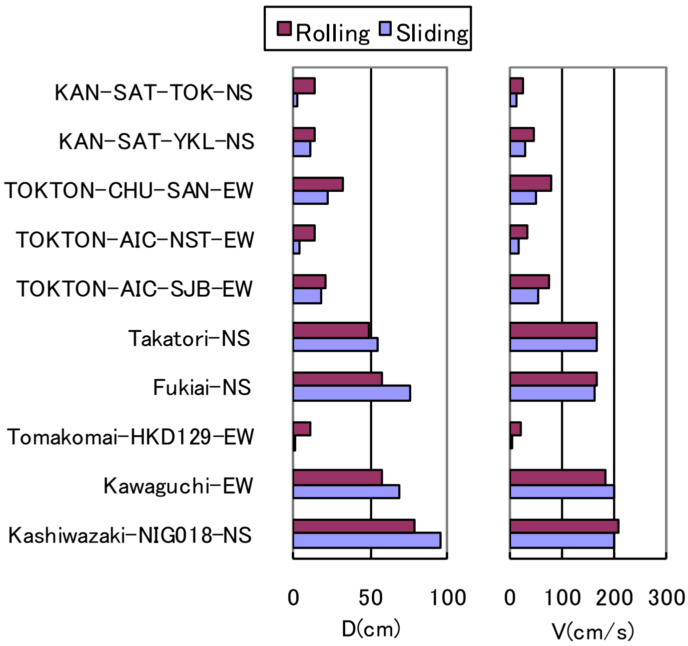



**Figure 3.1.** Maximum relative displacement and velocity response of isolated layer

## 4. MECHANISM AND CHARACTERISTICS OF VARIABLE OIL DAMPER

To keep a function of isolation during and after earthquakes, the isolators should be protected from failure or damage. In order to protect isolators from damage, the displacement response of isolators should be kept not to exceed the limit displacement of isolators. To reduce the response at isolated layer against earthquake motions with high velocity, following countermeasures should be considered.

a) To add kinds of shock absorbing devices
b) To add passive hydraulic damper

In case of shock absorbing devices, a research on the effectiveness of shock absorbing devices to reduce the displacement response was conducted. The shear force of the isolated layer with the devices is much larger than that without ones. (Iiba, et. al. 2008)

In this study, the research on adding passive hydraulic dampers for the countermeasure to reduce the response at isolated layer. The characteristics of damper are passively controlled with velocity. As shown in Fig. 4.1, when the relative velocity response at isolated layer is low, the damper keeps a low damping coefficient. When the relative velocity exceeds a certain value (Point P1 in Fig. 4.1), the damping coefficient is changed to high immediately.

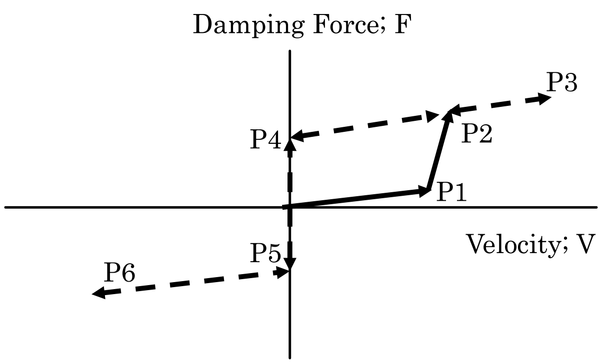



**Figure 4.1.** Force vs. velocity characteristics of variable damper

The variable oil damper for controlling the damping force was designed. As illustrated in Fig. 4.2, the oil flow is controlled by valve on-off switching according to the velocity of damper. In the low velocity, i.e. normal circuit, the oil in B area flows to C area through the brake valve. In case of high velocity in piston, i.e. emergency circuit, the pressure of oil in B area becomes high. As a result, the check valve will be open and the brake valve will be close. The oil flows through the relief valve.

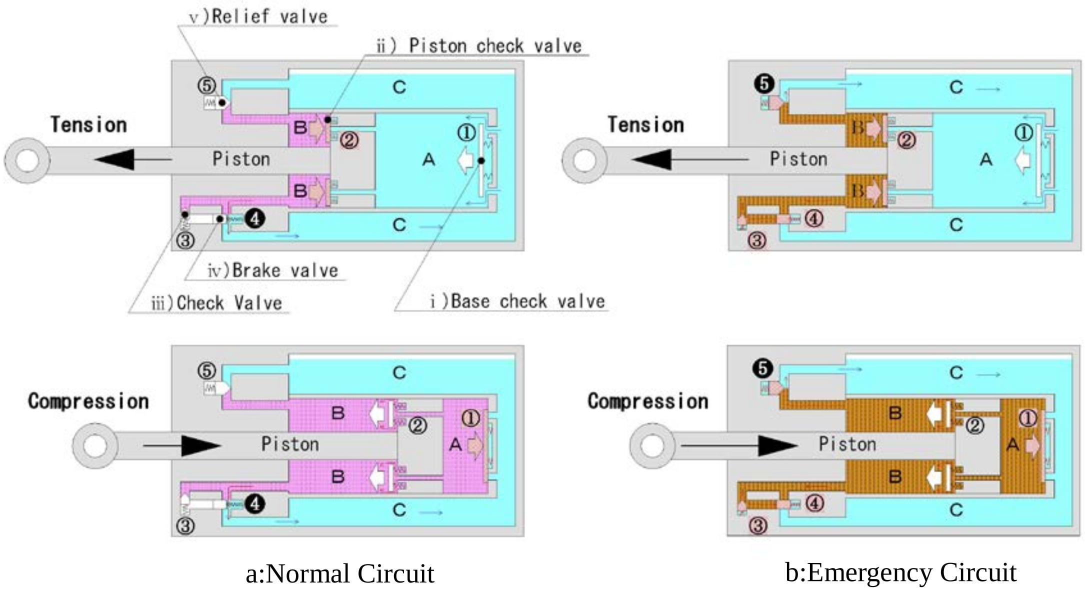



**Figure 4.2.** Structural component and oil flow of variable damper

For the parametric study in numerical calculation, values shown as Table 4.1 are set. These values are corresponding to the control points at damper characteristics as drawn in Fig. 4.3. At point P1, the damping coefficient is changed when the velocity exceeds $V_1$. The $V_1$ is set to 40 and 50 cm/s. And the damping force at point P2 is set to be 30 kN. The initial damping force; $F_1$ is set to be $F_2/30$ or $F_2/3$ when the velocity is less than $V_1$. The response of the model with $V_1$=50cm/s is compared among the number of dampers in Figs. 4.4 and 4.5. With increasing the dampers the displacement response at isolated layer is decreased. On the other hand, the displacement at 1st story is increased. When the number of damper is less than 2, maximum displacement at 1st story is less than 60mm (story drift angle; less than 1/45), and the safety of superstructure is kept. When 3 dampers are set to the system, maximum displacement is about 170mm (story drift angle; about 1/16).

**Table 4.1.** Parameters for numerical analysis

| | |
|---|---|
| Velocity; V (cm/s) | $V_1$=40, 50 $V_2=V_1+5$ $V_3$=100 $V_4$=5 |
| Damping force; F (kN) | $F_2$=30, $F_1=F_2/30$ or $F_2/3$, $F_3=F_2+C_3*(V_3-V_2)$, $F4=F_2-C_3*(V_2-V_4)$ |
| Damping coefficient; C(kNs/cm) | $C_1=F_1/V_1$, $C_2$=4.5, $C_3$=0.125, $C_4=C_2$ |
| Amount of dampers | 0.1W / F2, 0.2W / F2, 0.3W / F2<br>W:Total weight of seismically isolated house<br>When W is 300kN, above values are 1, 2, 3, respectively. |

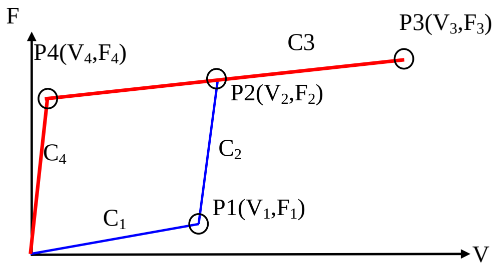



**Figure 4.3.** Control points of variable damper

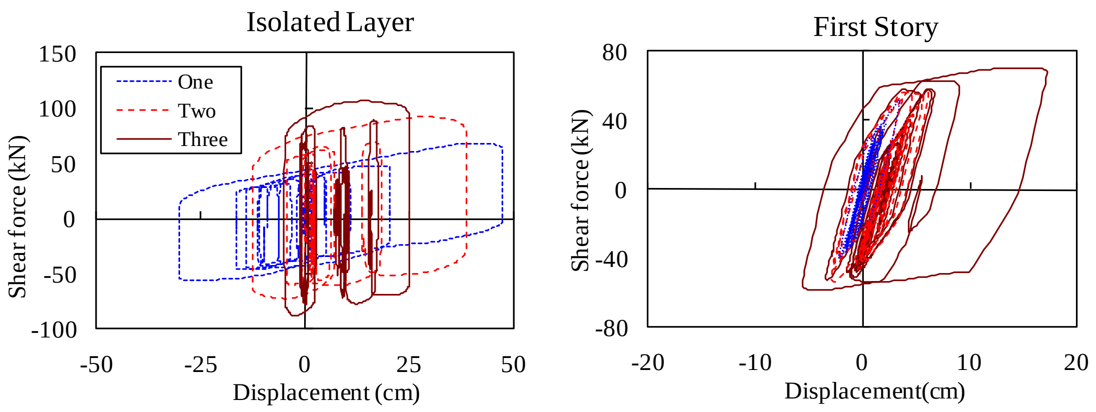



**Figure 4.4.** Shear force vs. displacement at isolated layer and 1st story (system; S-hv0, superstructure; trilinear, EQ : Tkatori-NS)

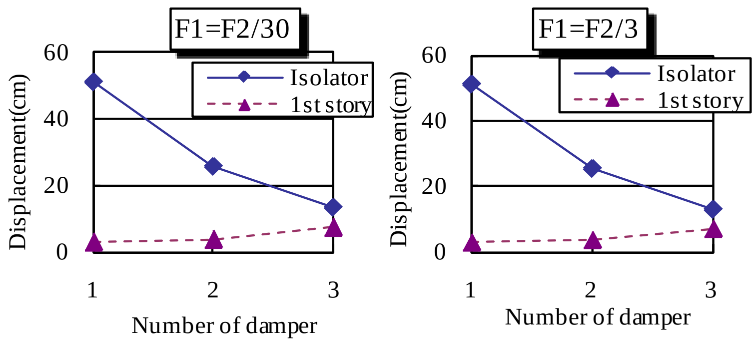



**Figure 4.5.** Maximum Displacement at isolated layer and 1st story (system; S-hv0, superstructure; trilinear, EQ : Kashiwazaki-NIG018-NS)

## 5. DYNAMIC TEST OF VARIABLE OIL DAMPER

### 5.1. Fundamental characteristics of damper

The manufactured variable damper is shown in Fig. 5.1 and Photo. 5.1. The total length of damper is 1,620mm and the stroke is 700mm. The damper is a uni-flow type, and the oil reservoir is set on the cylinder. To confirm the performance of the damper where the velocity exceeds 100m/s, a dynamic test using the shaking table is conducted, as shown in Photo. 5.1. The control points for the characteristics of the damper which are shown in Fig. 4.3, are P1(50cm/s, 10kN), P2(55, 73), P3(150, 77) and P4(20, 66.5).

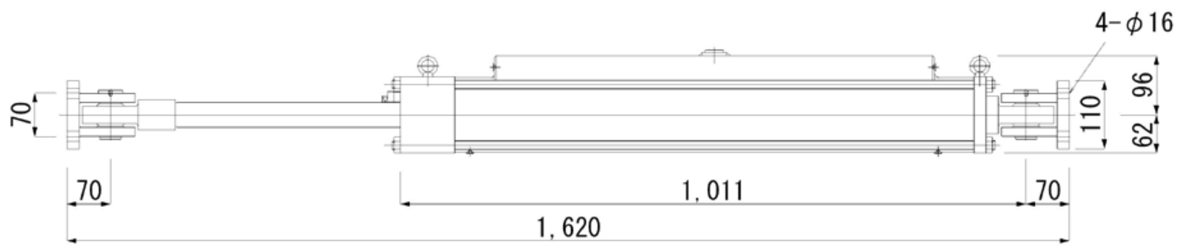



**Figure 5.1.** Schematic view of variable damper with dimensions

The forced displacement of sinusoidal wave (period: 1.53s) with maximum amplitude of 30cm (Max. velocity of 140cm/s) and increased with time is exerted to the damper, as illustrated in Fig. 5.2. Results of the performance of damper (force vs. displacement, force vs. velocity, etc.) are drawn in Fig. 5.3. The viscous coefficient of damper changed from low to high when the velocity exceeds 50 cm/s, and the damper keeps high damping force. After that, the pressure of damper gradually decreases, and the pressure returns to the low state in around three minutes.

**Photograph 5.1.** Schematic view of variable damper and dynamic performance test setup

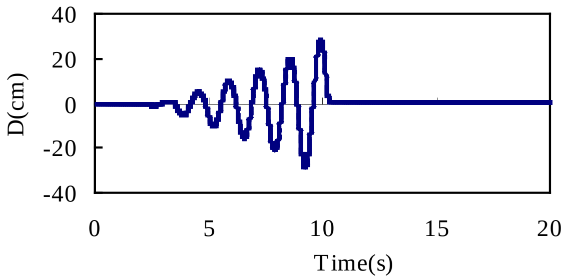
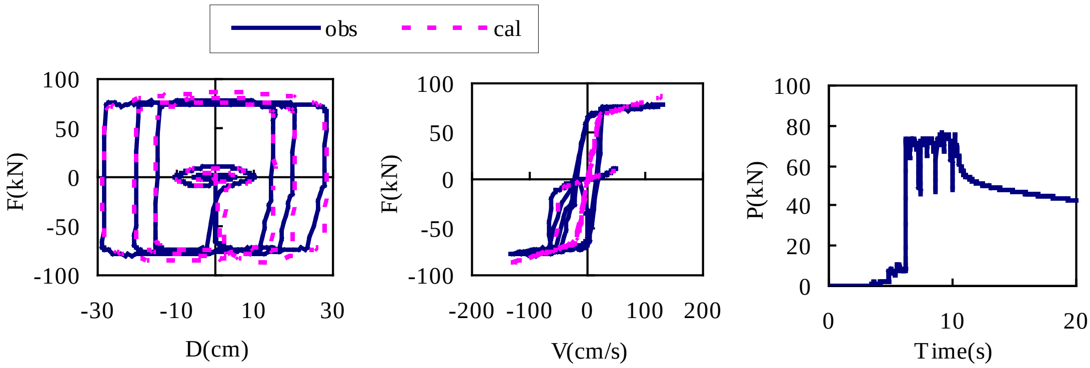



**Figure 5.2.** Waveform of forced displacement




a) Force vs. displacement b) Force vs. velocity c) Force with time for damper

**Figure 5.3.** Response against forced vibration with displacement

## 5.2. Shaking table test of seismically isolated model with damper

The shaking table test on a seismically isolated model with one room in plan is carried out, setting a variable damper at the isolated layer, as shown in Photo. 5.2. The control points for the characteristics of the damper are P1(50cm/s, 10kN), P2(55, 50), P3(150, 61.25) and P4(20,45.8). The relationships of force vs. displacement and force vs. velocity are drawn in Figs. 5.4 and 5.5, against sinusoidal motion ($D_{max}$=22.8cm, $V_{max}$=82cm/s, period=1s) and Takatori-NS motion (80% of original wave amplitude,

$D_{max}$=37.5cm, $V_{max}$=105cm/s) for input excitation respectively. The damper shows good performance that the high viscous force is kept after the relative velocity of the isolated layer exceeds 50 cm/s.

A :Seismically isolated model

b :Damper Setting

**Photograph 5.2.** Specimen and damper setting on shaking table test

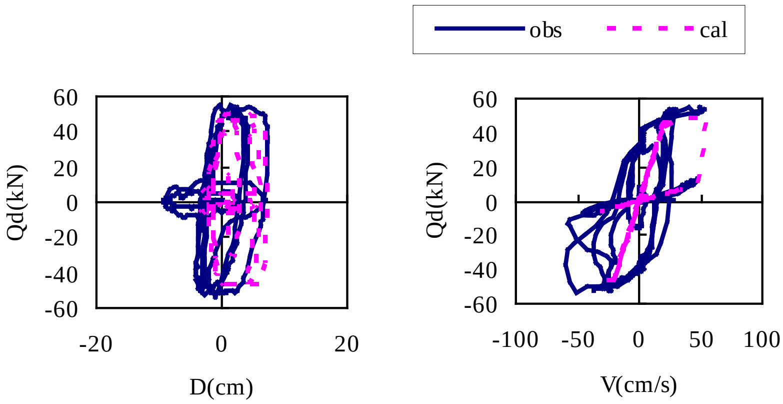



**Figure 5.4.** Result of shaking table test (Response against sinusoidal wave)

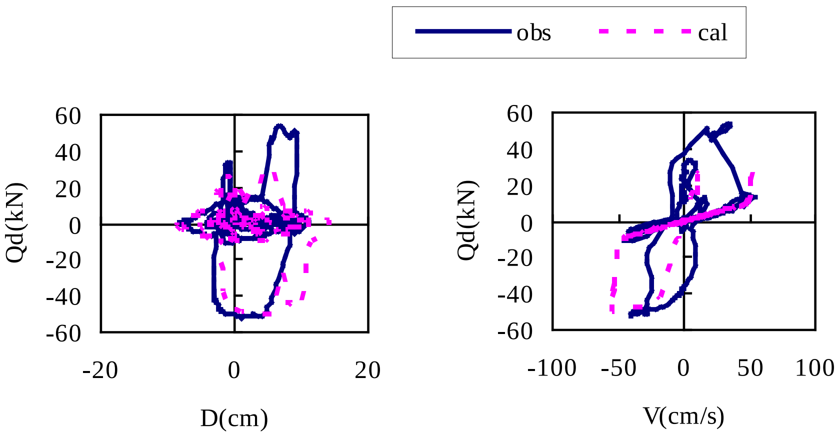



**Figure 5.5.** Result of shaking table test (Response against Takatori-NS Wave)

The time histories of displacement, velocity and force are drawn in Fig. 5.6, with comparison between experiment and simulation results during the Takatori-NS motion (80% of original wave amplitude). The seismically isolated model is assumed to be one mass model for simplicity of numerical calculation. The waveform of displacement response in the calculation is similar to that of the experiment. The maximum displacement at isolated layer is 10.9cm during the earthquake. In the model without the variable damper, maximum displacement is 41.1cm, which exceeds the design limitation in seismically isolated houses. The effect of damper on reduction of displacement is remarkable. On the other hand, the acceleration of superstructure becomes large and maximum acceleration of about 0.7G at the top of the model is observed. In order to confirm the effectiveness of the variable damper, it is necessary to clarify the relationship between the amount of reduction for displacement and that of increase for acceleration, by considering the amount of relief force and the appropriate relationship of viscous force vs. velocity.

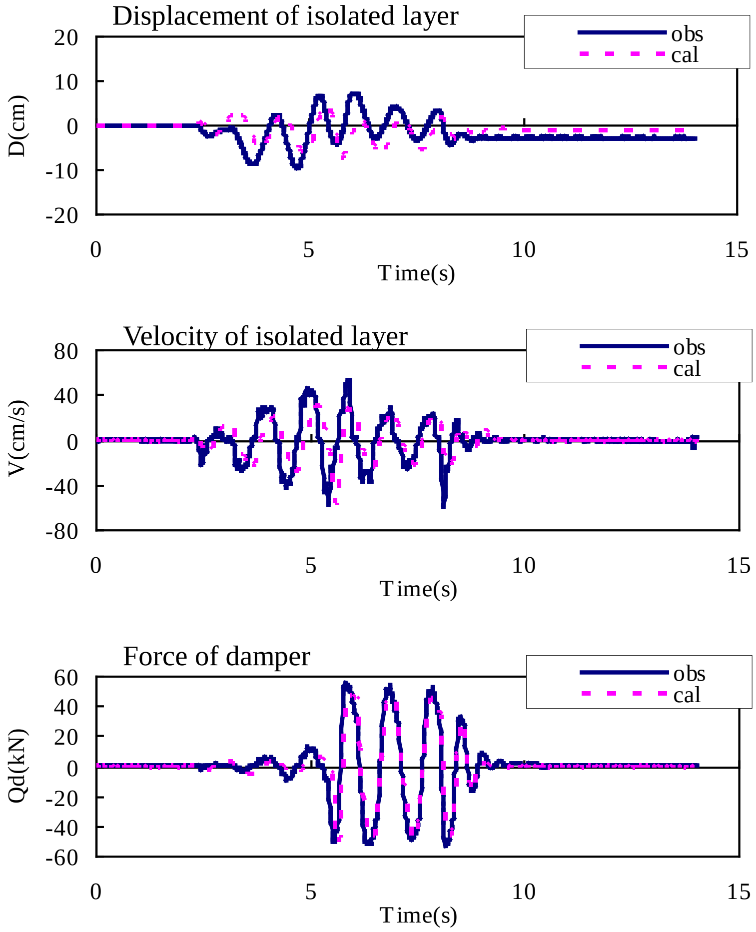



**Figure 5.6.** Comparison of time history between experiment and simulation results

## 6. CONCLUSIONS

To keep the function of isolation during and after earthquakes, the isolators should be protected from failure or damage. In order to protect isolators from damage, the displacement response of isolators should be kept not to exceed the limit displacement of isolators. To reduce the displacement response at isolated layer, the variable damper, whose viscous coefficient is passively changed by the velocity at isolated layer, is manufactured and dynamically tested. It is demonstrated that the variable damper shows the good performance. Through the shaking table test, the variable damper is effective to reduce the displacement response at isolated layer. On the other hand, the acceleration of superstructure becomes much large. In order to confirm the effectiveness of the variable damper, it is necessary to clarify the relationship between the amount of reduction for displacement and that of increase for acceleration, by considering the appropriate characteristics of damper.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## REFERENCES

Architectural Institute of Japan (2007), "Collected Material for predicted strong earthquake waves under trench-type huge earthquakes based on various predicted methods," (in Japanese)

Fujitani, H. et. al.(2008), "The Capability of the MR Damper Verified by Shaking Table Tests and Real Time Hybrid Tests," *Proceedings of 14th World Conference on Earthquake Engineering*, Paper No. 11-0088

Iiba, M., T. Hanai, M. Midorikawa, T. Azuhata and N. Inoue (2008), "Safety Evaluation of Seismically Isolated Houses with Displacement Restraint Devices under Severe Earthquake Motions," *Proceedings of 14th World Conference on Earthquake Engineering*, Paper No. 09-01-0082.

Japan Meteorological Agency, Strong Motion Waveform (2004 Mid-Niigata earthquake), downloading form JMA homepage.

Kurino, H., T. Yamada, J. Tagami and K. Shimizu (2002), "Semi-active structural control by switching oil damper with built-in controller", *Proceedings of 3rd World Conference on structural Control*, Vol.1, 211-216

Kurino, H., Y. Matsunaga, T. Yamada, and J. Tagami (2004), "High Performance Passive Hydraulic Damper with Semi-active Characteristics, " *Proceedings of 13th World Conference on Earthquake Engineering*, Paper No.33.

Kurino, H., T. Yamada, Y. Matsunaga, and J. Tagami (2006), "Switching Oil Damper with Automatic Valve Operation System for Structural Control," *Proceedings of 4th World Conference on structural Control and Monitoring*, Paper No.217.

Nakamura, Y., F. Uehan, and H. Inoue (1996), "Earthquake Motion Wave and its Analysis Observed in 1995 Hyogoken-Nanbu Earthquake, Part 2, " JR Earthquake Information, No.23d (Taktori Station, FD Serial No. R-004)

National Research Institute for Earth Science and Disaster Prevention, Kyoshin Network (K-NET) Database.

Osaka Gas (1995), digital data is provided by courtesy of Osaka Gas Co. LTD. (1995)

Yoshioka, H., J. Ramallo, and B. Spencer (2002), "Smart Base Isolation Strategies Employing Magnetorheological Dampers," *Journal of Engineering Mechanics*, ASCE, Vol. 128, 540-551.