STUDY ON A BASE ISOLATION SYSTEM

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SUMMARY

Authors composed a base isolation system to reduce horizontal seismic acceleration, which was named TASS system (TAISEI Shake Suppression system). This system is fundamentally composed of sliding bearings and horizontal spring beams. The response characteristics of the system were studied analytically, and the small scale model experiment was carried out on the shaking table. Based on these results, TASS system turned out to be effective to reduce the seismic horizontal acceleration response.

INTRODUCTION

In the investigation of the aseismic engineering, the resistibility of structures against earthquake motions has been made clear and increased through the analyses and experiments of the dynamic and static behaviours of them. On the other hand many base isolation systems have been investigated and developed to reduce the seismic force, some of which are now in use actually in New-Zealand, France and Japan. The mechanisms to reduce the seismic effects are roughly grouped into four types, base isolation type, energy dissipation type, soft spring type and automatic control type. TASS system belongs to the base isolation method, which also has the ability of energy dissipation in case of large deflection.

OUTLINE OF TASS SYSTEM

TASS system is composed of sliding bearings and horizontal spring beams as Fig. 1. Sliding bearings support the vertical loads on it and scarcely resist against horizontal force. Teflon or ball bearings are used for sliding bearings. Steel plates or bars are used for horizontal spring beams. Horizontal spring beams connect the sliding floor to the base frame or building floor, and add the small horizontal stiffness to the sliding floor.

Support conditions of the horizontal spring beams are fixed on one end and pin-roller on the other end. Period and yielding shear coefficient of TASS system are decided by the size of section and length of horizontal spring beams. Horizontal seismic force is mitigated by the following two mechanisms.

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1) Long period characteristics of TASS system which eliminates response acceleration especially in the short period range.
2) Plastic energy dissipation of horizontal spring beams which reduces the response when the deflection of the beams become large.

DYNAMIC CHARACTERISTICS

Stiffness Characteristics

Stiffness characteristics of the system are composed of that of horizontal spring beams and friction of sliding bearings. Stiffness characteristics of horizontal spring beams can be idealized as bi-linear type as Fig. 2. Stiffnes of sliding bearings is composed of static friction and kinetic friction, and re presented by rigid-plastic type as Fig. 3. The stiffness, strength and period of the system can be expressed as follows.

1) Elastic stiffness of horizontal spring beam:
$K=3EI/\ell^3$.......(1) K: elastic stiffness E: Young's modulus
I: geometrical moment of inertia
ℓ: beam length
2) Yielding shear force of the beam:
$Qy = Z\cdot\sigma_y/\ell$.....(2) Qy: yielding shear force
Z : section modulus σ_y: yield strength
3) Yielding shear coefficient:
$C_D=Qy/W$.........(3) C_D: yielding shear coefficient
W : weight
4) Period of TASS system:
$T=2\pi\sqrt{W/(g.k)}$...(4) T: period k: elastic stiffness
g: gravity acceleration

Using the above four equations, beam length can be decided by the next equation.

$$\ell = \frac{T}{2\pi}\sqrt{\frac{3}{2}\cdot\frac{E}{\sigma_y}\cdot t\cdot C_D}\ ...(5)\qquad t: \begin{cases}\text{steel bar diameter}\\ \text{steel plate thickness}\end{cases}$$

Number of steel bars or plates is given by the next equation.

$$n = \frac{W\cdot C_D\cdot\ell}{\sigma_y\cdot Zo}\ ....(6)\qquad Zo:\ \text{section modulus} = \begin{cases}\frac{\pi t^3}{32} & \text{steel bar}\\ \frac{bt^2}{6} & \text{steel plate (b: width)}\end{cases}$$

Yielding deflection is given by the next equation.

$$\delta y = \frac{2\cdot\sigma_y\cdot\ell^2}{3\cdot E\cdot t}\ ....(7)$$

Damping Characteristics

Damping of the system is mainly generated by the energy dissipation of friction of the bearings and plastic deformation of the lateral springs.

Damping factor of plastic energy dissipation is expressed as follows.

$$h = \frac{1}{2\pi}\cdot\frac{\Delta\varepsilon}{\varepsilon}\ ....(8)$$

$\Delta\varepsilon$: plastic energy dissipation
ε : elastic strain energy

Damping factor of kinetic friction energy dissipation is given by the nex equation.

$$h = \frac{4}{\pi}\frac{Qdf}{K\cdot\delta}\ ....(9)$$

Qdf: Kinetic friction force

In case that C_D=0.1, Qdf=0.01, $\delta=\delta y$, damping factor is calculated as $h=\frac{4}{\pi}\cdot\frac{0.01}{0.1} = 0.127$.

VIBRATION ANALYSES OF TASS SYSTEM

Modeling of the Building and Calculation of Floor Response Waves

The vibration model of the building in which TASS system was set actually is shown in Fig. 4. An important equipment was set on the ninth floor of the building and TASS system was selected to secure its safety against earthquakes. The first story of the building is composed of reinforced concrete frame and the upper stories are composed of steel frame with bracing. As the stiffness of the first story is so rigid that the analytical model is fixed at the second floor and has four lumped masses representing upper structure. Natural period and participation function of this model are shown in Fig. 5. By inputting EL-CENTRO 1940 NS and HACHINOHE 1968 NS to the base of the model, floor response waves of ninth floor were obtained as shown in Fig. 6. Maximum acceleration values of two input waves were normalized to 250 Gal, and the building were assumed to behave in the elastic range. Damping of the building model was assumed as frequency-proportional with the first modal damping factor of 0.03.

Modeling of TASS System and Seismic Response Calculation of Rigid Model

(1) Modeling of TASS system

TASS system was modeled as Fig. 7. At first isolated object and sliding floor were considered to be rigid. Vibration analyses were done on the next four assumptions.

1) Yielding shear coefficient (C_D) of horizontal spring beams is 0.1.
2) Natural period of TASS system is assumed as 1.5 sec which is three times of the first natural period of the building.
3) Stiffness characteristics is assumed as bi-linear type.
4) Frictional damping of the bearings and horizontal spring beams is substituted by equivalent viscous damping of h=0.1 for the first mode.

The model constants of TASS system are shown in Table 1.

(2) Seismic response of TASS system

By inputting floor response waves of Fig. 6 to TASS system model, isolation effects were examined. Input maximum accelerations were chosen as 375 Gal and 500 Gal. The results are shown in Table 2. The mitigation ratios of maximum accelerations are about 1/4 and the isolation effect of TASS system turned out to be very valid. It was also confirmed that the effect of plastic energy dissipation of horizontal spring beams is valid for the mitigation of the response.

Lumped Mass Model of Isolated Object and its Response Characteristics with TASS System and without TASS System

(1) Lumped mass model of isolated object

For grasping the actual response characteristics, isolated object was represented by the elastic one mass model. First natural period and modal damping factor were decided by the free vibration test data of the actual object.

Stiffness was calculated by the next equation

$$K = (2\pi/T)^2\cdot(W/g) \quad ......(10)$$

K: stiffness W: weight
g: gravity acceleration

Model constants are shown in Table 3.

(2) Response of one mass model of isolated object without TASS system

Floor response waves of Fig. 6 were normalized to 100 Gal and inputted to the base of one mass model. Response results are shown in Table 4. Maximum response acceleration of isolated object without TASS system is about 10 times of input a maximum acceleration.

(3) Response of one mass model of isolated object with TASS system

Combining the model of TASS system of Table 1 and that of isolated object of Table 3, coupled two masses model was made. Schematic figure of this model is shown in Fig. 8 and model constants are given in Table 5. In calculating the response, input maximum accelerations of floor response waves were chosen as 375 Gal and 500 Gal. Response results are shown in Table 6. Response maximum acceleration ratios of sliding floor to input maximum acceleration are $0.25 \sim 0.34$ and those of isolated object to input maximum acceleration are $0.66 \sim 1.15$. By comparing the maximum response acceleration of isolated object with TASS system and without TASS system, acceleration mitigation effect of TASS system was judged to be $1/9 \sim 1/14$.

VIBRATION EXPERIMENT BY SHAKING TABLE

General

(1) Purpose of the experiment

To make clear the isolation effect of TASS system experimentally, model specimen was vibrated by a shaking table. Specimen was designed according to the scale rule. The purposes of this experiment are composed of next five items.

1) To grasp the isolation effect of TASS system by the mitigation ratio of maximum response acceleration.
2) To confirm that the response displacement is smaller than the allowable value.
3) To know the difference of isolation effect according to the kinds of sliding bearings and horizontal spring beams.
4) To know the difference of response characteristics according as the isolated object is rigid or flexible.
5) To detect the items excluded from vibration analyses and important in the actual application.

(2) Kinds of experiment

Small scale models of isolated object and sliding floor with TASS system were set on the shaking table, and floor response waves and sin-waves were input. Specimens were 1/4 scale model by length.

Following varieties were incorporated in the specimens.

1) Rigid or flexible models of isolated object.
2) Sliding bearings by teflon or by ball bearings.
3) Horizontal spring beams by steel bars or by steel plates.

Method of Experiment

(1) Shaking table specification and input waves

Specification of the shaking table used in the experiment is shown in Table 7. Input floor response waves are shown in Fig. 9, whose time axes were shortened to 1/4 of actual motion and long period ingredients were filtered out to satisfy the displacement limitation of the shaking table.

(2) Specimen

Reduced scale specimen was made of steel and was composed of isolated object, sliding floor, TASS system and base frame. Scale law is shown in Table 8. Schematic figure of TASS system and flexible isolated object model are shown in Fig. 10.

(3) Measurement

The layout of pick-ups is shown in Fig. 11. Acceleration, displacement and strain were measured.

Results

To show the characteristics of the isolation effects, maximum response accelerations and their ratios are shown in Table 9 in case of HACHINOHE. Maximum deflections of horizontal spring beams are also shown in the table. In comparison with Table 9, maximum responses in case without TASS system are shown in Table 10. An example of response acceleration waves of shaking tablle, sliding floor and isolated object are shown in Fig. 12.

Consideration of Experiment Results

1) In case of rigid model, response acceleration ratios of sliding floor to shaking table were 0.16 ∿ 0.18.
2) In case of flexible model, response acceleration ratios of sliding floor to shaking table were 0.21 ∿ 0.32, and larger than above case. This is considered to be the influence of the vibration of the isolated object.
3) Response maximum acceleration ratios of isolated object to shaking table were 1.1 ∿ 1.62 with TASS system, and that without were 20 ∿ 22.6. The response acceleration mitigation ratios are calculated to be 1/14 ∿ 1/18, which reveals that the TASS system has very large isolation effect.

CONCLUSION

It was made clear that TASS system has good isolation effects and mitigates response acceleration to 1/9 ∿ 1/18 compared with the case without TASS system.

ACKNOWLEDGEMENT

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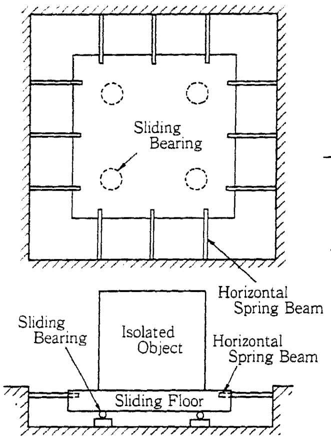

Fig. 1 Schematic Figure of TASS System

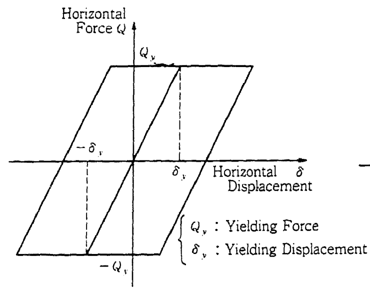

Fig. 2 Force Displacement Relationship of Horizontal Beams

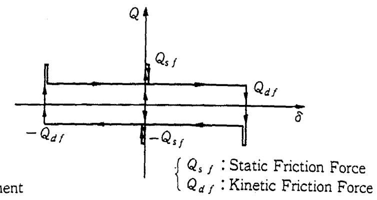

Fig. 3 Force Displacement Relationship of Sliding Bearings

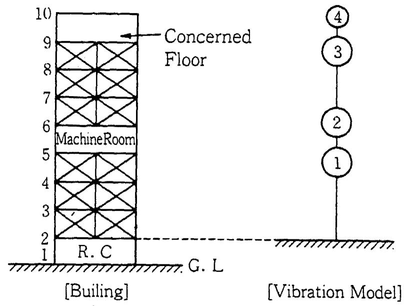

Fig. 4 Modeling of the Building

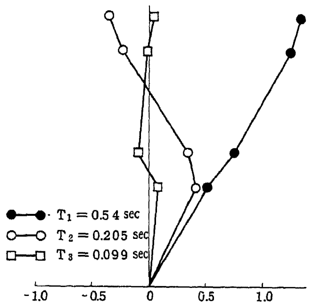

Fig. 5 Periods and Participation Functions of the Building

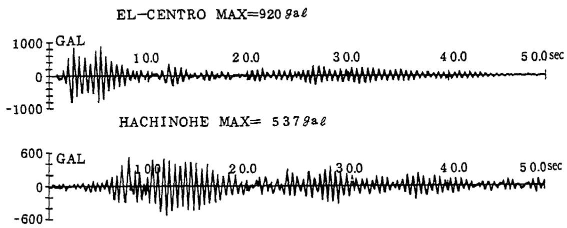

Fig. 6 Floor Response Waves (9th Floor)

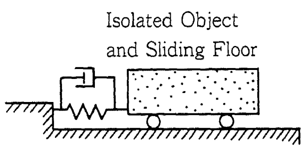

Fig. 7 Analytical Model of TASS System

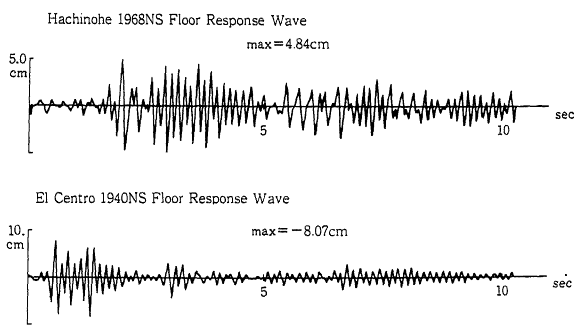

Fig. 9 Input Waves to Shaking Table

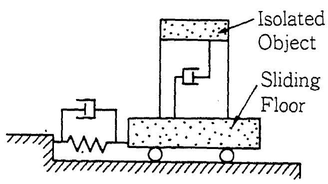

Fig. 8 Two Mass Model of TASS System and Isolated Object

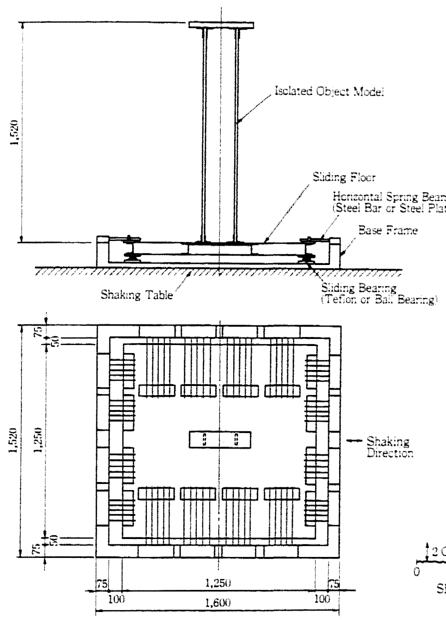

Fig. 10 Schematic Figure of TASS System and Isolated Object Model

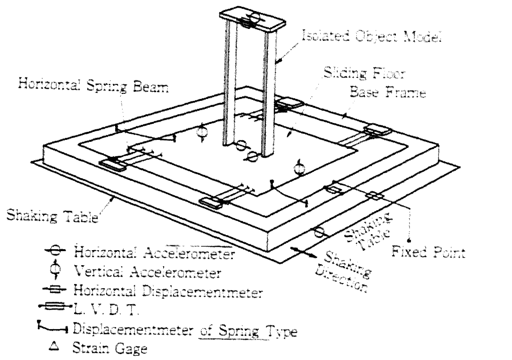

Fig. 11 Schematic Figure of Measurements

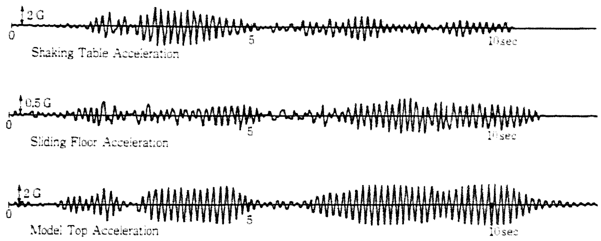

Fig. 12 Measured Acc. Wave of Two Mass Model of Isolated Object and TASS System

Table 1 Analytical Model Constants of TASS System

Weight	15000kg
Elastic Stiffness	268.56kg/cm
Yield Load	1500kg
Yield Disp.	5.59cm
Plastic Stiffness	0kg/cm
Damping Factor	0.10

Table 3 Isolated Object Model Constants

	Height	Period	Weight	Stiffness	Damping factor
Constant	608cm	0.526sec	2350kg	342kg/cm	0.0234

Table 4 Response Results of one Mass Model of Isolated Object without TASS System

Input Wave	Input Max. Acceleration (Ratio)	Response Max. Acceleration (Ratio)	Response Max. Displacement
HACHINOHE Floor Response	100 gal (1.0)	1063 gal (10.63)	7.46 cm
EL-CENTRO Floor Response	100 gal (1.0)	938 gal (9.38)	6.57 cm

Table 2 Response Results of One Mass Model of TASS System

Input Wave		CASE I	CASE II
HACHINOHE Floor Response	Input Max. Acceleration	375 gal (1.0)	500 gal (1.0)
	TASS System Acceleration (ratio)	142.5 gal (0.38)	154.1 gal (0.31)
	TASS System Displacement (D.F.)	7.1cm (1.27)	9.4cm (1.68)
EL-CENTRO Floor Response	Input Max. Acceleration	375 gal (1.0)	500 gal (1.0)
	TASS System Acceleration (ratio)	99.4 gal (0.27)	138.9 gal (0.28)
	TASS System Displacement (D.F.)	5.3cm (0.95)	7.9cm (1.41)

D.F.: Ductility Factor

Table 5 Two Mass Model Constants of Isolated Object and TASS System

Isolated Object Model	Weight	2350kg
	Stiffness	342kg/cm
	Period	0.526 sec
	Damping Factor	0.0234
TASS System Model	Sliding Floor Weight	12650kg
	Elastic Stiffness	268.56kg/cm
	Yield Disp.	5.59cm
	Plastic Stiffness	0kg/cm
	Damping Factor	0.10

Table 6 Response Results of Two Mass Model

Input Wave		HACHINOHE Floor Response		EL-CENTRO Floor Response	
Max Acc.		375 gal (1.0)	500 gal (1.0)	375 gal (1.0)	500 gal (1.0)
Resp. Max. Acc.	Sliding Floor (ratio)	129 gal (0.344)	156 gal (0.312)	95 gal (0.253)	144 gal (0.288)
	Isolated Object (ratio)	432 gal (1.152)	556 gal (1.112)	246 gal (0.656)	356 gal (0.730)
Resp. Max. Disp.	Sliding Floor (D.F.)	6.6 cm (1.18)	9.0 cm (1.61)	5.0 cm (0.89)	9.5 cm (1.70)
	Isolated Object	9.4 cm	10.6 cm	6.5 cm	7.3 cm

D.F.: Ductility Factor

Table 7 Condition of Shaking Table

Shaking Table	Horizontal one-component Size: 2m x 1.5m Max. weight: 5 ton
Vibration Condition	Max. displacement: 75mm Max. velocity: 61cm/sec Max. acceleration: 1.5G for zero load Frequency range: 0.1 to 30Hz
Input Wave	Sin wave Random time history

Table 8 Relationship of Prototype and Model

		Actual Scale	Scale Factor	Small Scale
Horizontal Spring Beam	Young's Modulus	2.1 x 10^6kg/cm^2	(1)	2.1 x 10^6kg/cm^2
	Steel Plate Thickness	12mm	($\frac{1}{4}$)	3mm
	Steel Bar Diameter	25mm	($\frac{1}{4}$)	6mm
	Yield Acc. (C_D)	0.1G	(4)	0.4G
	Period	1.5sec	($\frac{1}{4}$)	0.375sec
Sliding Floor Weight		12650kg	($\frac{1}{64}$)	197.7kg
Rigid Model	Weight	2350kg	($\frac{1}{64}$)	36.7kg
Flexible Model	Weight	2350kg	($\frac{1}{64}$)	36.7kg
	Period	0.526sec	($\frac{1}{4}$)	0.132sec
	Stiffness	342kg/cm	($\frac{1}{4}$)	85.5kg/cm
	Height	608cm	($\frac{1}{4}$)	152cm
	Damping factor	0.0234	(1)	—

Table 9 Experimental Results of Two Mass Model of Isolated Object and TASS System

Hor. Beam	Steel Bar				Steel Plate			
Bearing	Teflon		Ball Bearing		Teflon		Ball Bearing	
Model	Rigid	Flexi-ble	Rigid	Flexi-ble	Rigid	Flexi-ble	Rigid	Flexi-ble
Shaking Table Acc. (Ratio)	1529 (1.0)	1999 (1.0)	1803 (1.0)	1784 (1.0)	1862 (1.0)	1823 (1.0)	1921 (1.0)	1960 (1.0)
Sliding Floor Acc. (Ratio)	259.7 (0.17)	416.5 (0.21)	245.0 (0.14)	470.4 (0.26)	333.2 (0.18)	588.0 (0.32)	303.8 (0.16)	563.5 (0.29)
Model Top Acc. (Ratio)	-	2195 (1.10)	-	2116 (1.18)	-	2960 (1.62)	-	2940 (1.50)
Beam Max. Deflection (D.F.)	0.55cm (0.39)	0.62cm (0.44)	0.58cm (0.41)	0.65cm (0.46)	0.70cm (0.50)	0.60cm (0.43)	0.60cm (0.43)	0.60cm (0.43)

D.F.: Ductility Factor

Table 10 Experimental Results of One Mass Model of Isolated Object without TASS System

Input Wave	HACHINOHE Floor Response	EL-CENTRO Floor Response
Shake Table Max. Acc. (Ratio)	450 gal (1.0)	500 gal (1.0)
Model Top Max. Acc. (Ratio)	10150 gal (22.6)	10000 gal (20.0)