(3) as a function of the sliding velocity based on experimental investigation:

$$\mu = \mu_{max} - (\mu_{max} - \mu_{min}) \cdot exp(-a \cdot |x_d|) \quad (3)$$

where a is a parameter defining the relationship between the friction coefficient and sliding velocity (0.2 sec/cm in this analysis), μ_{min} is the friction coefficient in low velocity range (8% in this analysis), and μ_{max} is the friction coefficient in high velocity range (20% in this analysis).

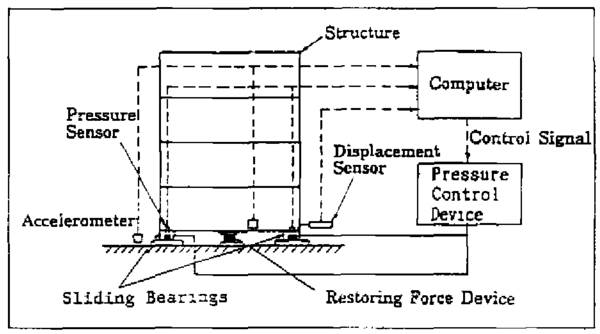
Excellent agreement is observed in experimental and simulation results. Figure 9 gives an example which compares the response time histories obtained from the simulation and testing under the same Kaihoku earthquake motion with peak acceleration of 0.544g. The simulation and test produced almost the same peak response values and similar time histories. Therefore, the proposed analytical model represented by Eqs. (1) - (3) can be reliably used in evaluating the key seismic response quantities. This model is simple and efficient, and thus it is useful in designing bridges isolated by the sliding system

Frictional Controllable Sliding Isolation Systems for Buildings

Coefficient of friction equal to 20% or somewhat larger, as in the system presented above, is considered to be reasonable when used to design bridge sliding isolation systems. An isolation system with such a high value of coefficient of friction is totally ineffective for small to moderate earthquakes with peak ground acceleration less than 20% (or even somewhat larger value) of g. This is usually no cause for concern for bridge structures. However, building floor acceleration response to such small to moderate earthquakes can be amplified and easily cause damage to sensitive equipment, valuable items and secondary systems inside the building. Reducing coefficient of friction can reduce building response acceleration but will produce large sliding displacement on the building base, causing safety problems. A friction controllable sliding isolation system was developed to solve such problems associated with sliding isolation systems applied to buildings.

System Configuration

The proposed sliding system using friction controllable bearings (FCB's) is conceptually depicted in figure 10 with a building structure supported by the bearings. Each bearing has a fluid chamber that is connected to a pressure control system composed of a servo valve, an accumulator and a computer.The friction force on the sliding interface between the bearing and the foundation is controlled by adjusting the fluid pressure in the chamber through the use of computer control techniques. The computer calculates an appropriate signal to control the fluid pressure based on the observed structural response, such as response acceleration and sliding displacement, and sends the signal to the pressure control device.



■ Figure 10
Concept of hybrid sliding isolation system for buildings

The idealized section view of the prototype friction controllable sliding bearing is shown in figure 11. The steel disk-shaped bearing contains a fluid chamber which is sealed by a rubber O-

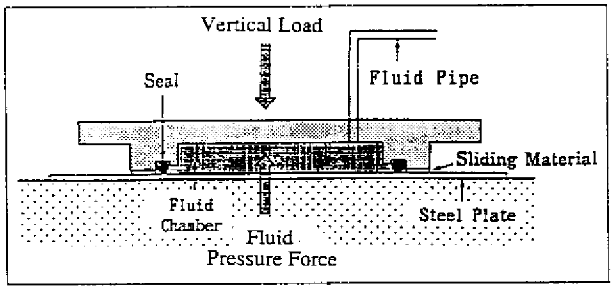


Figure 11
Idealized view of friction controllable sliding bearing

ring around the circular perimeter of the fluid chamber just above the sliding interface. A sliding material, such as a Teflon-based material, is placed on the sliding surface.

This semi-active isolation system has the following general advantages; (a) Changing friction force through controlling pressure requires a very little amount of energy and power than the corresponding actuator-driven active base isolation system, and as a consequence (b), the use of accumulators for the source of energy is possible, thus eliminating the necessity of an emergency energy supply system, and (c) it can serve as a passive function base isolation device if everything fails.

Control Algorithm

Control of structural response by the proposed semi-active sliding isolation system using friction controllable bearings presents a unique problem in developing control algorithms for the following reasons. The control force in this sliding system is the friction force, which depends on the direction of the sliding velocity and thus enters as a nonlinear term into the equation of motion. For controlling such a nonlinear force, standard control theory is difficult to apply. In this study, an optimal control algorithm was developed based on the instantaneous optimal control theory.

The instantaneous optimal control algorithm is derived based on the time dependent objective function given as follows, aiming at controlling both floor response accelerations and sliding displacement of the building base:

$$J(t) = qdx1(t)^2 + qff(t)^2 + ru(t)^2 \tag{4}$$

where f is the normalized frictional coefficient $(f(t) = \mu(t)g)$, x_1 is the sliding displacement of the building base floor with respect to the foundation, u is the pressure control signal, and q_d, q_f, and r are non-negative weighting coefficients. Under the assumption that the building motion will always remain in the sliding phase with the help of control, the following equation of motion of an n-story shear building in the sliding phase is used as a constraint.

$$\ddot{x}(t) = Ax(t) + B\dot{x}(t) + cf(t)sgn(\dot{x}_1(t)) + d\ddot{z}(t) \tag{5}$$

where, $x = [x_1, x_2, \ldots xn]^T$

$$A = \begin{bmatrix} -\frac{k_2}{m_1} & \frac{k_2}{m_1} & \ldots & 0 \\ \frac{k_2}{m_2} & -\frac{k_2 + k_3}{m_2} & \ldots & 0 \\ \ldots & \ldots & \ldots & \ldots \\ 0 & \ldots & \frac{k_n}{m_n} & -\frac{k_n}{m_n} \end{bmatrix},$$

$$B=\begin{bmatrix} -\frac{c_2}{m_1} & \frac{c_2}{m_1} & \cdots & 0 \\ \frac{c_2}{m_2} & -\frac{c_2+c_3}{m_2} & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots \\ 0 & \cdots & \frac{c_n}{m_n} & -\frac{c_n}{m_n} \end{bmatrix}$$

$$c=\left[-\frac{m_s}{m_1},0,\ldots,0\right]^T,\ d=\left[-1,-1,\ldots-1\right]^T \tag{6}$$

in which $m_s = m_1 + m_2 + \ldots + m_n$

Another set of constraints are the relationships among the pressure control signal u, the chamber pressure p and the friction f. They are as follows:

$$T\dot{p}(t)+p(t)=u(t) \tag{7}$$

$$f(t)= -c_1 p(t) + c_2 \tag{8}$$

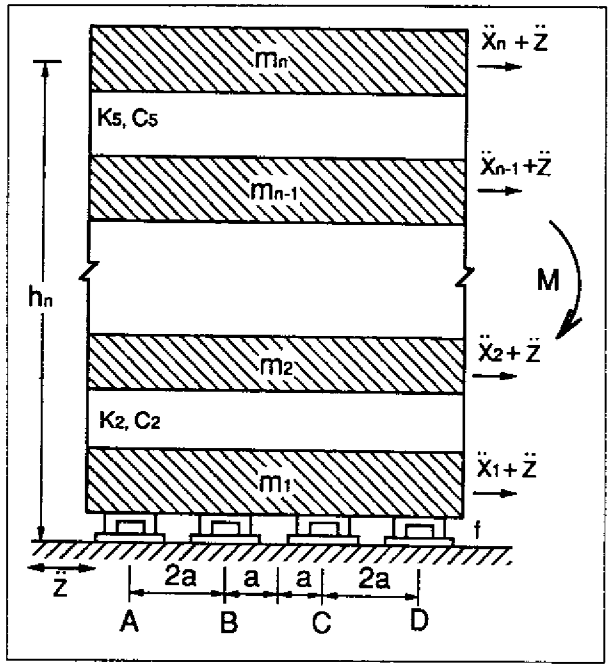
where T, c_1 and c_2 are constants.

The numerical solutions of Eqs. (5), (7) and (8) are used as constraints to the objective function $J(t)$. Omitting the lengthy derivation for optimization, the optimal pressure control signal is derived as

$$u(t)=F_f f(t)+F_d x_1(t)sgn\left(\dot{x}_1(t)\right) \tag{9}$$

where F_f and F_d are feedback gains.

When applying the proposed sliding isolation system to buildings, in which the friction force is controlled by changing the fluid pressure in the bearing chamber, the problem of uplifting could become a serious issue for the following reasons:



■ **Figure 12**
Analytical model

If the uplifting force (to be defined below) increases to the extent that the vertical load on a bearing becomes smaller than the pressure force therein, the bearing will be uplifted, permitting the fluid to escape, and the friction controllable bearing will cease to function. Therefore, it is necessary to study the problem of uplifting to ensure that the control algorithm is properly modified to eliminate the problem.

The uplifting force is generated by the overturning moment M resulting from the building response acceleration. Assuming that eight bearings are installed in two rows and thus the building is supported by four sets of two bearings each denoted as A, B, C, and D and the distance between the adjacent two bearings is $2a$, the uplift forces, P_A, P_B, P_C, and P_D can be calculated by the following equations (see figure 12);

$$\frac{1}{2}M=\frac{1}{2}\sum_1^n\left(m_1\left(\ddot{x}_i+\ddot{z}\right)h_i\right) \\ =3aP_A+aP_B-aP_C-3aP_D \tag{10}$$

$$P_A = 3P_B,\ \ P_C = -P_B,\ \ P_D = -P_A \qquad (11)$$

where, h_i is the height of i-th floor. The vertical loads W_A, W_B, W_C, and W_D acting on each of the bearings A, B, C, and D become:

$$W_A = \frac{1}{8} m_s g + P_A,\ W_B = \frac{1}{8} m_s g + P_B,$$
$$W_C = \frac{1}{8} m_s g + P_C,\ W_D = \frac{1}{8} m_s g + P_D \qquad (12)$$

Under the overturning moment, W_A, W_B, W_C, and W_D are obviously different from each other. Therefore, the maximum pressure force to be provided at the bearing chambers cannot be larger than the minimum value among the vertical loads acting on these bearings divided by λS, if chamber parameters are to be controlled to the same value:

$$u(t)_{max} = \frac{Minimum\left(W_A, W_B, W_C, W_D\right)}{\lambda S} \qquad (13)$$

where S is the vertical projected area of the fluid chamber of each bearing, and λ is a safety coefficient larger than unity.

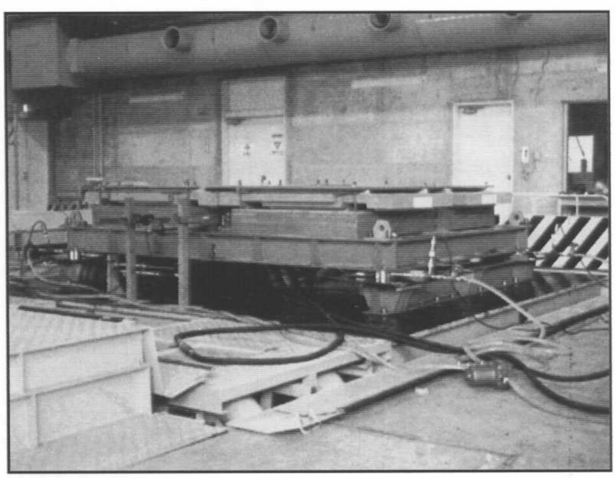


Figure 13
Structure model with hybrid sliding isolation device in experiment

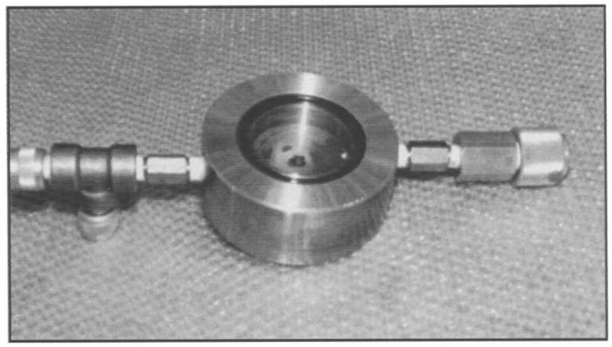


Figure 14
Friction controllable sliding bearing for experiment

Since the vertical load on each bearing is a function of floor response accelerations, $u(t)_{max}$ takes a different value at every time instant according to the response acceleration. Therefore, as long as the control signal u is checked and confined below the $u(t)_{max}$ at every time instant, uplifting of the bearing can be prevented.

Shaking Table Test

A structural model, representing a rigid structure which weighs 12 tonf, was supported equally by four friction controllable sliding bearings and tested on a shaking table, as shown in figure 13. Figure 14 is the photo of the bearing used in the experiment. The bearing, with a brass sheet of 1 mm thickness attached to be used as sliding surface, slides on a stainless steel plate fixed on steel I-bars bolted down on the shaking table. Furthermore, a rubber O-ring of 5.7 mm in diameter serves to seal the fluid in the fluid chamber. The area of the sliding surface is 86.0 cm^2, and the vertically projected area of the fluid chamber is 57.7 cm^2. No restoring force device is used in order to study the effect of friction force only. A servo valve is located at the center of the experimental structure from which the pressurized fluid is distributed to each sliding bearing.

In the computer control system, the controller is a 16 bit microcomputer (80286) with a nu-

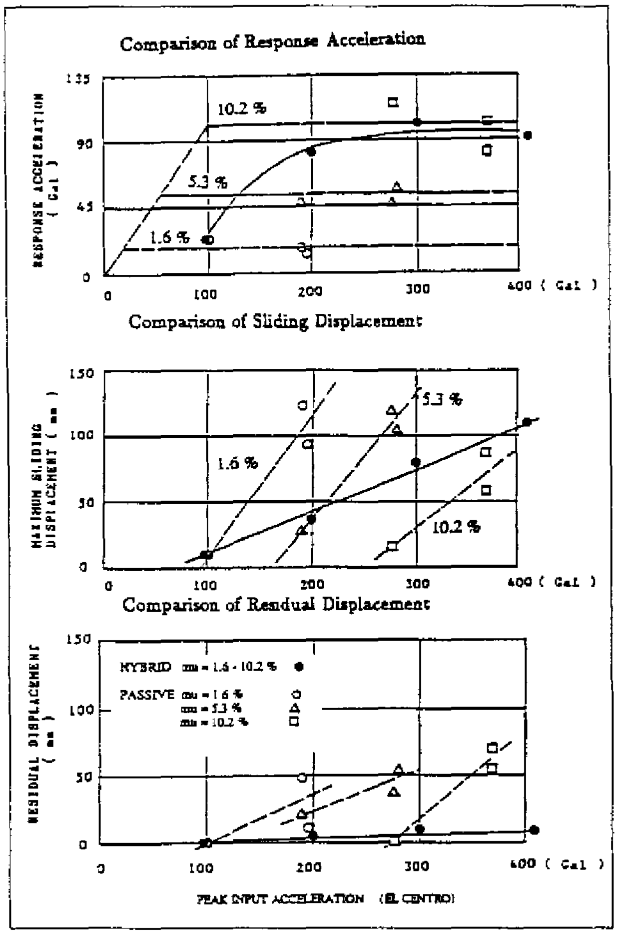


Figure 15
Comparison of passive and hybrid isolation

merical co-processor (80287) to facilitate faster computation. The response signals for feedback purpose are measured by sensors and sent to the microcomputer through a 12-bit A/D converter. Then, the control signal is calculated according to the feedback control algorithm described earlier, and sent to the servo valve and servo amplifier through a 12-bit D/A converter to control the fluid pressure in the bearing chamber. A computer code for control implementation in experiments is developed using the C language.

Sensors were placed to monitor (1) the accelerations on the shaking table and in the structural model, (2) relative displacement between the shaking table and the model, and (3) fluid pressure at each fluid chamber and at the servo valve. The acceleration of the structure and the sliding displacement were used for feedback control purpose.

The shaking table experiments were conducted under one-dimensional horizontal motion. The El Centro (1940) record was used as ground input motion for most of the experiments, by linearly adjusting the maximum acceleration to different levels. Hachinohe and Taft earthquakes as well as sinusoidal waves were also used in some of the tests.

The performance of the friction controllable isolation system is compared to that of the corresponding passive isolation system Figure 15 shows the maximum response acceleration, maximum sliding displacement, and the residual displacement of the structural model with passive and controllable isolation systems under the El Centro earthquake with different peak ground accelerations. The dashed lines represent the passive isolation systems with three different coefficients of friction, namely 1.6%, 5.3%, and 10.2%, whereas the solid line represents the controllable isolation system in which the coefficient of friction is controlled between 1.6% and 10.2%.

In the passive isolation, if a small friction coefficient, for example 1.6%, is used, a high level of isolation performance is expected since the response acceleration is reduced to a low level In this case, however, the maximum displacement becomes excessive very rapidly as the input earthquake intensity increases. On the other hand, if a large friction coefficient, such as 10.2%, is used, the sliding displacement can be confined within a relatively small range. However, the isolation performance in this case is limited in the sense that the acceleration cannot be satisfactorily reduced Particularly for small to medium earthquakes with peak acceleration less than 100 gal, this passive sliding isolation system does not function at all, thus the response acceleration remains equal to the input acceleration. Such acceleration might damage sensitive equipment inside the building.

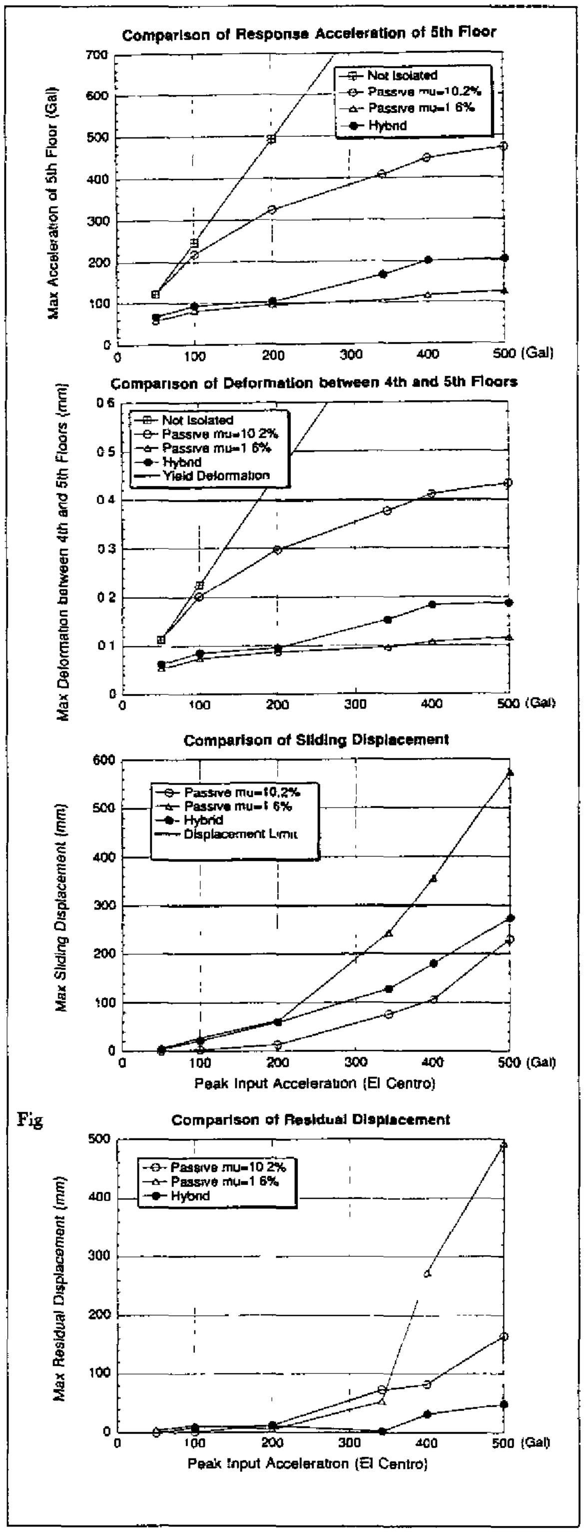
The controllable isolation system, however, can alleviate the problems associated with the passive isolation system. For small to medium earthquakes, the friction can be controlled to a very small level to make the structure slide easily, so that the response acceleration can be considerably reduced. For large earthquakes, the friction is controlled to prevent excessive sliding displacement, while the response acceleration can also be kept at a low level. Another advantage of the semi-active system is clearly seen in figure 15 where the residual sliding displacement can be maintained at almost zero level.

Numerical Example

Since the uplift force tends to narrow the range of the controllable pressure, its effect on the control performance is of concern. Simulation study was conducted to investigate such effect which was covered on the shaking table testing. An existing office building, called the J Building, located in Taisei Technology Research Center in Yokohama, Japan, was used as a example for this simulation. This four-story office building is currently constructed on a passive sliding base isolation system (TASS system), consisting of eight sliding bearings and a number of rubber springs. The coefficient of sliding friction is designed at 10% and the spring stiffness is designed in such a way that the fundamental period of the building is 5 seconds.

This study assumes that earthquake ground motion is one-dimensional either in the longitudinal or transverse direction. Since the simulation results obtained separately for the two directions are quite similar, only the results in the long cross-sectional direction will be presented in this paper.

The J Building can be idealized with a five-degree-of-freedom shear model. The values of masses, stiffness, and damping coefficients associated with the building in the longitudinal direction, as well as the building dimensions are given in (Feng, 1993). The damping coefficient for each



■ **Figure 16**
Comparison of non-isolation, passive and hybrid isolation

story is assumed to correspond to a classically damped structure with a damping ratio of 3% for the first vibration mode. In order to examine only the effect of the friction, neither a spring nor a damper is used between the building base and the ground in this analysis

Assuming that the friction controllable bearings with the same characteristics as identified in the previous experiments (Feng, Shinozuka and Fujii, 1993 and Feng, 1993) are installed in the J Building to replace the existing passive system. the same analytical models also with the same parameter values shown in reference (Feng, Shinozuka and Fujii, 1993 and Feng, 1993) were used for the numerical simulation

The effectiveness of the controllable sliding system was investigated under earthquakes with various intensities, by comparing the seismic responses of the building under the controllable isolation with those under the passive isolation or without isolation. For this purpose, the passive systems with two different coefficients of friction, 10.2% and 1.6, are used, while the hybrid system controls the coefficient of friction between 1.6% (approximately) and 10.2% (the feedback gains used are F_f = 1.0 kgf s^2 / cm^3 and F_d = -3.3 kgf / cm^3 and the safety coefficient is λ = 1.2). For the input acceleration, earthquakes with different intensities obtained by linearly scaling the El Centro (1940) record are used The maximum values of the top floor response acceleration, top story deformation, base sliding displacement, and residual displacement for the buildings not isolated, passively isolated and isolated by the semi-active isolation system are compared in figure 16

The following observations are made. (1) For the non-isolated building, the response acceleration and interstory deformation increase proportionally with the intensity of the input earthquake, and thus they may become too large to be tolerated, when earthquake intensity becomes severe. For example, under the earthquake with peak acceleration around 180 Gal, yielding will occur at the top story However, in the sliding isolation system, the earthquake intensity is irrelevant to the response acceleration and interstory deformation which depend on the coefficient of friction on the sliding interface. This is an advantage of sliding isolation system. (2) For a passive system, if the coefficient of friction is small, the response acceleration and deformation will also be small, indicating a good isolation performance, but the base sliding displacement tends to become unacceptably large as the input acceleration becomes large. On the other hand, if the large coefficient of friction is used, the sliding displacement can be reduced, but the isolation performance becomes poor, especially when the intensity of input earthquake motion is very small. Also, in the case of 10.2% coefficient of friction, yielding will occur under the peak input acceleration of 390 Gal. Therefore, it is very difficult, if not impossible to design a passive sliding isolation system to be effective for earthquakes with all levels of intensity (3) For the controllable system, however, for small to medium earthquakes with peak acceleration below 100 Gal, the coefficient of friction is kept at a minimum value to obtain the best possible isolation performance. For large to strong earthquakes, the friction is controlled to confine the sliding displacement to the acceptable range, and at the same time the response acceleration and interstory deformation are under certain levels which are much smaller than the corresponding values for the comparable passive system with coefficient of friction 10% Therefore, this semi-active sliding isolation system is very versatile and effective for all earthquake intensity levels. (4) For small to large earthquakes, practically no residual displacement is produced. Even for strong earthquakes of rare occurrence, the residual displacement can be controlled to as small as 5 cm. (5) In general, the control performance is not adversely influenced by the overturning moment, thus the proposed semi-active control can greatly reduce floor response acceleration

Conclusion

Two types of sliding isolation systems were presented, a passive system for bridge use and a friction controllable system for building application. The following conclusions are obtained:

For the passive isolation system:

■ The advantage of sliding isolation systems was confirmed on a large scale bridge model with flexible piers by shaking table testing and numerical simulation. That is, the deck acceleration and pier shear force of the bridge isolated by a sliding system are limited to constant values regardless of intensities of input ground acceleration.

■ There was practically no residual displacement in the sliding isolation system after each earthquake.

■ A simple, reliable, and efficient analytical method was developed which can be used for design purposes.

For the friction controllable isolation system:

■ Significant advantages of the friction controllable sliding isolation system were demonstrated, for small to medium earthquakes, the friction is controlled to make the building slide easily to reduce the transfer of the seismic force to the building to a minimum, and as the input earthquake becomes more intense, the friction is controlled to confine the sliding displacement of the structure to an acceptable range, while at the same time to keep the transfer of seismic force under an acceptably low level Such intelligent features of the friction controllable system make the sliding isolation system effective for all intensities of earthquakes.

■ The instantaneous optimal control algorithm, developed for control of the friction force which has a nonlinear feature, has proved to be effective in achieving the desired control performances. In addition, they are practical and easy for real-time and on-line control operations.

■ Little adverse effect of the overturning moment was observed on the control performance, indicating that the semi-active system can be applied also to moderately slender buildings.

■ The reliability of this system can be more easily tested and established through field experiences than the passive sliding isolation system since this system has much more opportunities of being activated under smaller earthquakes, which will occur more frequently.

Personnel and Institutions

In June 1993, an NCEER-Taisei Collaborative Research Agreement entitled "Structural Control of Bridges and Building Structures" was signed between NCEER and Taisei Corporation. The research involved NCEER Princeton investigators, led by M. Shinozuka and University at Buffalo investigators led by M. Constantinou. Taisei Corporation provided technical personnel, existing passive sliding bearings, and experimental structural models, and also facilitated the use of their shaking table for experimentation This article describes the research that was performed jointly by Princeton researchers and Taisei engineers primarily on friction control bearings. In addition to carrying out the passive sliding base isolation test on a bridge model, the joint research team modified Taisei's existing passive sliding bearings to make them friction controllable, developed semi-active control algorithms and verified the effectiveness of the modified bearings and algorithms by shake table test.

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