Development of Passive and Semi-Active Sliding Bearings

by Masanobu Shinozuka and Maria Feng

Abstract

Design and construction of buildings, bridges and other constructed facilities to satisfy their performance criteria such as life-safety, durability and human comfort under severe environmental conditions such as strong earthquakes have been the challenge to the civil engineer. The recent emergence of high-tech materials and precision instrumentation techniques are playing an important role in responding to this challenge on the part of the civil engineer. Utilization of active, semi-active and hybrid (including base isolation) control techniques to confine the structural response within the response criteria has begun to be recognized as a viable alternative to designing and constructing structural systems strong enough to perform under the worst possible loading conditions.

This study demonstrates that friction base isolation systems, especially those equipped with a friction controllable device, offer more desirable base isolation characteristics. This demonstration was done through experimental analytical and numerical effort, by developing sliding base isolation systems with and without friction controllable devices and by verifying their base isolation capabilities for bridges and buildings through shake table tests and a numerical simulation study

For bridges, passive sliding base isolation systems were primarily used. The shake table experimental results strongly suggested that the deck acceleration and pier shear force of the bridge isolated by a sliding system can be confined to constant values independent of intensities of input ground (shaking table) acceleration In particular, with the rubber restoring device installed, there was no residual displacement in the sliding system after each earthquake. It was also shown that numerical simulation is highly reliable and can be used for design purposes.

For buildings, friction controllable base isolation systems were tested, analyzed, and used for semi-active control of building motion. The advantage of the friction controllable sliding isolation system was such that, for small to medium earthquakes, the friction is controlled to make the building slide easily so that the transfer of the seismic force to the building is minimized For stronger earthquakes, the friction is controlled to confine the sliding displacement of the structure to an acceptable range and at the same time the transfer of seismic force can be kept under an acceptable level. The control of the friction force can be achieved by means of the instantaneous optimal control algorithm which is implementable for real-time and on-line control operations Finally, it is important to note that the reliability of this system can be more easily tested and established through field experiences than the passive sliding isolation system, since this system is more likely to be activated under smaller earthquakes which occur more frequently.

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Objectives and Approach

The objective of this study was to demonstrate, by shake table tests and numerical simulations, that sliding bearings are viable base isolation systems for both bridges and buildings. This study shows that, with the aid of an innovative bearing device that was developed, the bearing system can be used as a semi-active device for more efficient and possibly optimal base isolation performance.

The effectiveness, robustness and maintainability of base isolation systems, whether elastomeric or sliding, must be demonstrated by experiments. In addition, mechanical and other properties of various key components of the device must be experimentally identified and, if necessary, analytically checked. These identified properties describe the mechanical and other behaviors of the device which are needed for its analytical model in the process of reproducing the experimental result. Such reproducibility is vital for the design of base isolated structures. The technical as well as conceptual approach this study has taken follows these general principles. Special care has been exercised to design, fabricate and test an innovative friction controllable bearing, which is the key to a friction controllable base isolation system that provides the structural engineer with semi-active control options for base isolated structures.

This task is part of NCEER's Bridge Project (now the Highway Project). The task number is 91-5411A.

Accomplishments

Sliding base isolation technology has been applied in civil structures such as buildings and bridges with increasing popularity. Sliding isolation systems produce the isolation effect by limiting the seismic force transmitted to the structure across the isolation interface and by absorbing earthquake energy. They are characterized by insensitivity to the frequency content of earthquake ground motion and stability.

While sliding isolation systems have already found wide application in many bridges, not much large scale dynamic testing of bridge sliding isolation systems has been conducted, especially for bridges with flexible piers. In order to study the dynamic characteristics of sliding-isolated bridges, a sliding isolation system was developed and experimental and analytical studies were carried out (Feng and Okamoto, 1994 and Okamoto, 1994). This isolation system is composed of sliding bearings with coefficient of friction 20% on the sliding isolation interface and rubber restoring force devices. The experimental study included shaking table testing of a 40-ton bridge model with flexible piers. Several earthquake records and design earthquakes with different intensities and frequency contents were used as input motions in the test. The dynamic characteristics of the sliding system was identified first by the loading test and then confirmed by the shaking table test. Numerical simulation capability, with satisfactory accuracy, of the response of actual bridges equipped with this sliding isolation system is also important for the design of the bridges thus isolated. For this purpose, a simple and efficient numerical model based on the direct integration method was proposed. The advantages of the sliding isolation system is demonstrated here not only by the shaking table test but also by means of numerical simulation.

Different from bridge isolation, the purpose of building isolation is usually to protect not only the structure but also its occupants and vibration-sensitive internal equipment from low to moderate earthquake acceleration. This requires a sliding isolation system with a relatively small coefficient of friction as opposed to a bridge system, in which case it is usually 20% or larger. The small coefficient of friction, however, will limit the capacity of energy dissipation and will result in correspondingly large sliding displacements. Such a large sliding displacement might be excessive enough to cause collision of the building with adjacent buildings. Restoring force devices may help to bring the structure back to its original position after earthquakes, but they are not usually effective in reducing the sliding displacement.

To overcome this difficulty, a friction controllable isolation system for building applications was developed and experimentally and analytically studied (Feng, Shinozuka and Fujii, 1993 and Feng, 1993). This innovative system provides a variable friction force which is computer-controlled by changing the pressure in a fluid chamber of the bearing. A prototype system was developed, and tested on a shaking table using a 12-tonf structural model (representing a rigid building) equipped with this system. Control algorithms, especially developed for controlling the frictional force which has an inherent nonlinear feature, were used in this study, and their effectiveness was verified. A reliable analytical model was developed by carefully comparing numerical simulation results to experimental results. Effects of overturning moments acting on a building were numerically investigated. A four-story office building was used as an example for numerical analysis. Experimental and numerical studies demonstrated that, compared to its conventional passive counterparts, the friction controllable sliding isolation system thus developed is more effective in controlling both the seismic force transmitted to the building and the sliding displacement for earthquakes with a broad range of intensity.

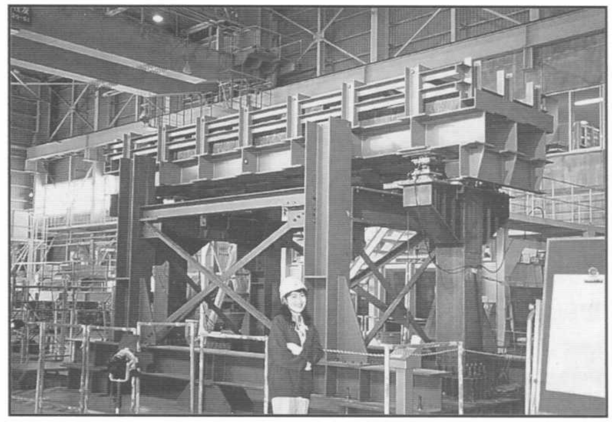


Figure 1
Bridge model

Sliding Isolation System for Bridges

The bridge model used in the shaking table test is shown in figure 1. The bridge span, the pier height, and the deck weight are 6.0m, 2.5m, and 390 kN respectively. The fundamental natural period of the bridge is 0.48 seconds when the girder is supported by piers through a fixed bearing on one end and a roller bearing on the other.

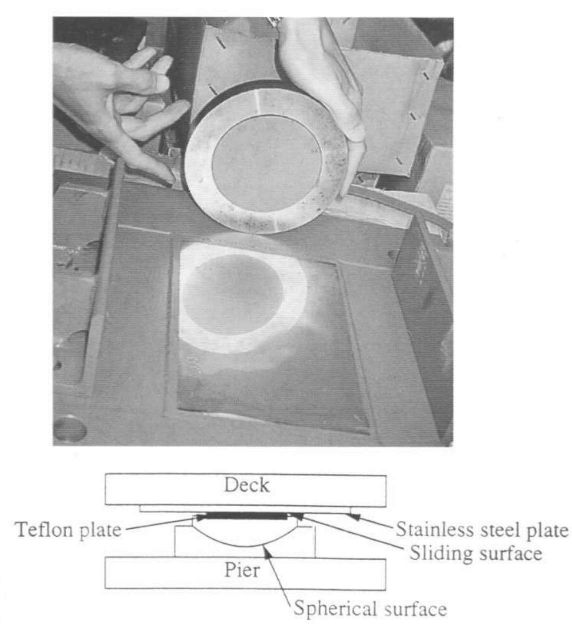
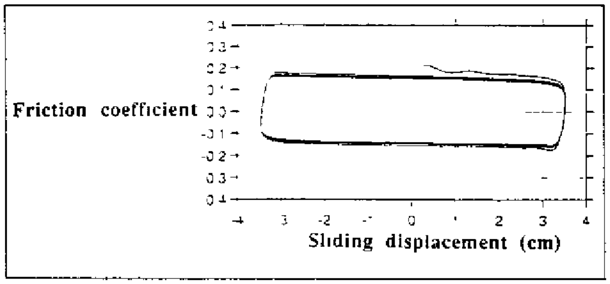


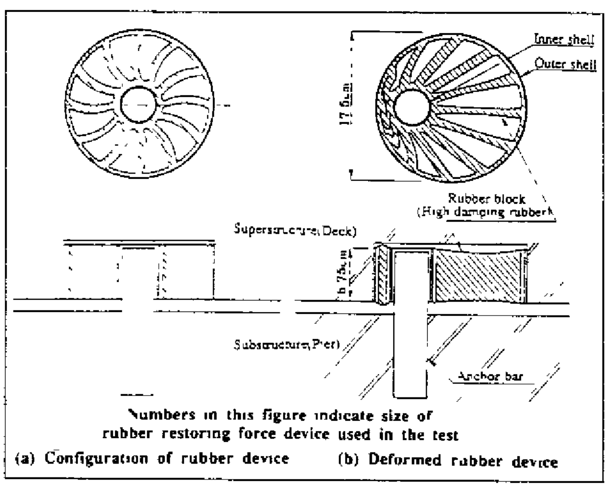
Figure 2
Detail of sliding bearing



■ Figure 3
Example of identification test [Maximum sliding velocity: 200 cm/sec]

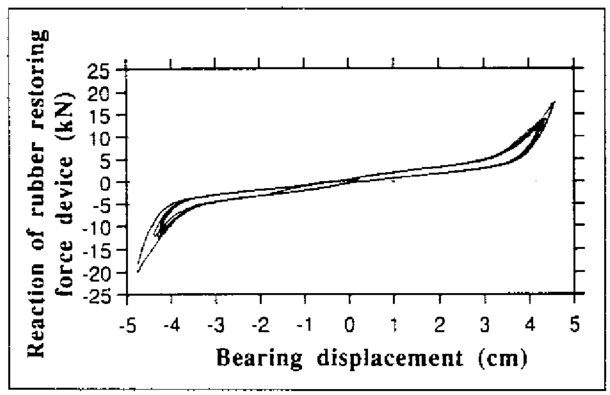
The passive sliding type isolation system was developed and equipped on this bridge. Two sliding bearings and a rubber restoring device were installed on each pier with the rubber device located in the middle of two sliding bearings. In total, therefore, four sliding bearings and two rubber restoring devices were used for the model.

As shown in figure 2, the sliding bearing consists of a stainless steel plate attached to the deck and a circular Teflon plate (diameter = 10 cm) fixed on the pier through a bearing plate. The bearing plate has a semi-spherical surface which can rotate freely from the pier deformation to keep the Teflon plate in horizontal and in perfect contact with the steel plate A load cell is installed between the bearing and the pier to measure the vertical load on the bearing. The pressure on the sliding surface of the Teflon plate is evaluated as 12.4 MPa. Figure 3 shows a typical relationship between the friction coefficient and the sliding displacement observed during a loading test carried out prior to the shaking test The velocity dependency of the friction coefficient was also experimentally investigated (Feng and Okamoto, 1994 and Okamoto, 1994). The average friction coefficients at low and high velocity range of the bearing were found to be 8% and 20% respectively.



■ Figure 4
Rubber restoring force device

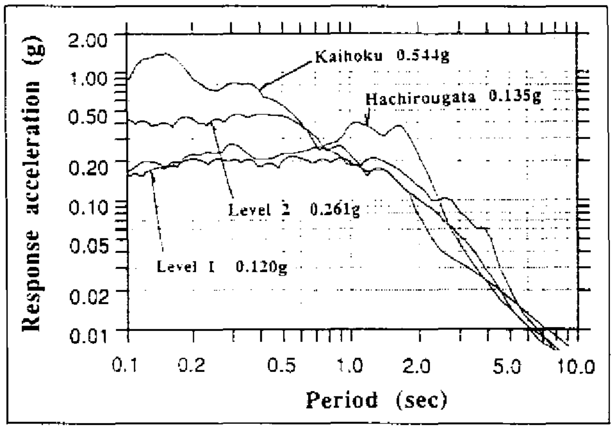
Figure 4 depicts the rubber restoring force device, which consists of a rubber block and an anchor bar. Figure 5 indicates the force-displacement relationship of the rubber restoring force device obtained from a loading test. The device works as a horizontal spring within a small displacement range, and serves as a displacement restrainer when the displacement approaches a certain limit. The natural period evaluated from the weight of the deck (390 kN) and the stiffness of the device (1.32 kN/cm) is 2 44 seconds.



■ Figure 5
Force displacement relationship of rubber restoring force device

Shaking Table Test

Two earthquake records (Kaihoku and Hachirougata) and two artificial design motions (Japanese Level 1 and Level 2 earthquake motions on ground condition II - stiff soil) were used in the test. As shown in their response spectra in

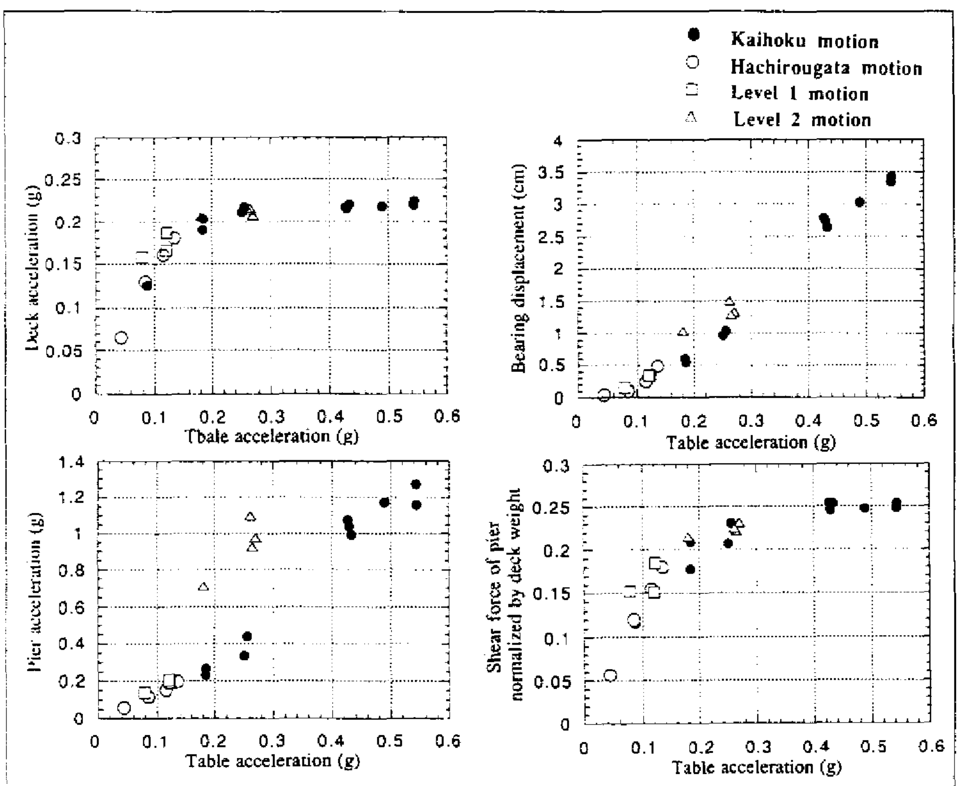


■ **Figure 6**
Response spectra of input motions

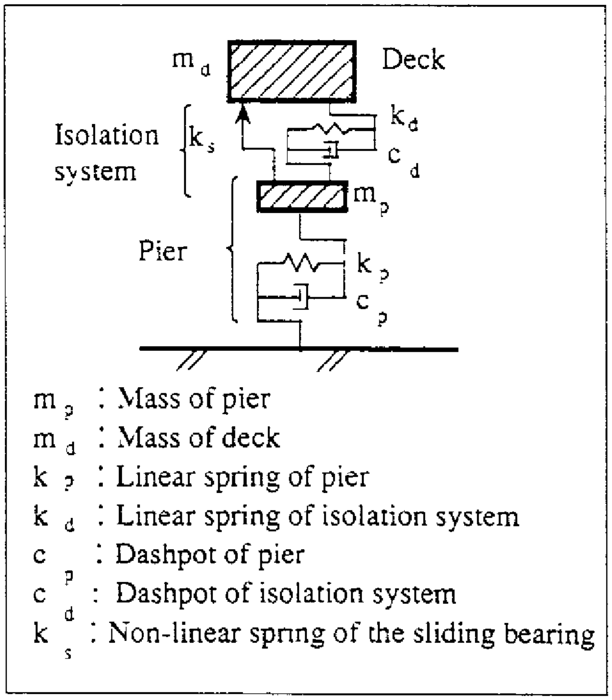
figure 6, these motions have different intensities and frequency contents. Due to the limited displacement capacity of the shaking table, however, it was not possible to use the earthquake motions with large intensities for the shaking table test. Therefore, the Hachirougata and Level 2 motions were used after scaling them down linearly by a factor of approximately 1/2 to 1/3, respectively. The shaking was applied only in the longitudinal direction.

Figure 7 shows the maximum values of the pier acceleration, deck acceleration, normalized shear force of the pier, and bearing displacement as functions of the maximum table acceleration. The pier acceleration and bearing displacement become larger as the table acceleration increases. However, the deck acceleration and normalized shear force of the pier remain constant at their respective maximum values beyond the table acceleration of 0.2g, regardless of the increase of table acceleration. This is the unique and significant advantage of the sliding base isolation system as applied to bridges. The maximum deck acceleration is 0.22g corresponding to the friction force plus the restoring force.

Permanent displacements were observed only under the Kaihoku and Hachirougata motions.



■ **Figure 7**
Maximum response of bridge model



■ **Figure 8**
Simulation model

Maximum response except for the permanent displacement occurred under the Kaihoku 0 544g input motion (Feng and Okamoto, 1994 and Okamoto, 1994).

Numerical Analysis

The analytical model depicted in figure 8 is used to simulate the dynamic behavior of the bridge during the shaking table testing. The discontinuous function $sgn(\dot{u}_d)$ in the governing equation of motion (1), which is usually used to express the friction force, is replaced by the analytical expression (2) for approximation,

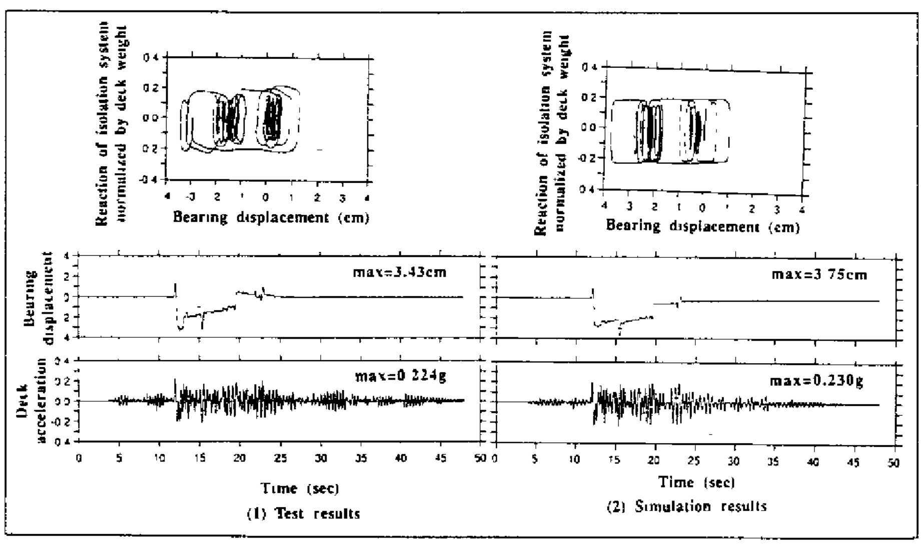
$$m_d\left(\ddot{z}+\ddot{x}_p+\ddot{x}_d\right)+c_d\dot{x}_d+k_dx_d = -sgn\left(\dot{x}_d\right)\mu m_d g \tag{1a}$$

$$m_p\left(\ddot{z}+\ddot{x}_p\right)+c_p\dot{x}_p+k_px_p-c_dx_d - k_dx_d = sgn\left(\dot{x}_d\right)\mu m_d g \tag{1b}$$

$$sgn\left(\dot{x}_d\right)\approx\frac{1+exp\left(-\delta\dot{x}_d\right)}{1+exp\left(-\delta\dot{x}_d\right)} \tag{2}$$

where $\ddot{z}$ is the ground acceleration (table acceleration), x_p is the displacement of pier relative to ground, x_d is the displacement of deck relative to pier (bearing displacement), k_d and k_p are stiffness of the isolation system and the bridge pier, c_d and c_p are damping coefficients of the isolation system and pier, δ is a parameter to define the shape of the function $sgn(x_d)$ in approximation (4.0 sec/cm is used in this analysis)

The friction coefficient μ is modeled in Eq.



■ **Figure 9**
Results of simulation