# PSEUDO DYNAMIC TESTS AND IMPLEMENTATION OF SLIDING BRIDGE ISOLATORS WITH VERTICAL MOTION

**Kazuhiro NAKAJIMA[1], Hirokazu IEMURA[2], Yoshikazu TAKAHASHI[3] And Kazushi OGAWA[4]**

## SUMMARY

A sliding seismic isolator that, due to its sliding property, cuts off the inertia force acting on the bridge pier is actively being developed. However, some concerns have been expressed about the performance of this isolator under the effect of vertical ground motions. As it is well known, the sliding bearings are velocity and vertical-load dependent; therefore, under the effect of vertical ground motions, the friction coefficient is expected to change greatly, affecting the horizontal earthquake response. In this study, pseudo-dynamic tests and numerical simulations are performed to analyze the effect of vertical seismic loads on the horizontal earthquake response characteristics of this sliding seismic isolator. The isolation system consists of a sliding bearing that generates the friction damping, and of a rubber bearing that generates the restoration force. A hybrid on-line earthquake response test is performed, in which the sliding bearing is exposed to a pseudo-dynamic loading test with vertical load variation. The sliding bearing is composed of a Teflon plate and a stainless steel plate on each sliding surface. The JMA Kobe record of the Hyogo Ken Nanbu Earthquake of January 17, 1995 is used as input load. Furthermore, a numerical analysis is also performed to confirm the effect of the vertical seismic load on the sliding seismic isolator.

From the results, it becomes clear that, although the friction force changes remarkably when the vertical ground motion is applied, the horizontal earthquake response presents little influence and almost no change is observed on it. The same behavior is observed even in the case where the vertical seismic load is scaled to larger peak values. The results also show that a better isolation performance is obtained reducing the rubber bearing stiffness of the isolator, since the cut off effect of the sliding bearing becomes more relevant. With the experimental results, implementation of the bearing to different type of bridge structures is investigated through numerical simulation.

## INTRODUCTION

The natural period of sliding seismic isolator can easily be extended because only the spring stiffness, friction damping, and the saturation of sliding inertia determine their natural frequency. These bearings, with a rigid metal sliding bearing, do not sink or produce microvibrations while supporting vertical loads on actual bridges.

A sliding seismic isolator with sliding bearings and horizontal springs are thought to have an identical seismic isolation effect as that from conventional base isolation bearings (LRB). However, when subjected to vertical motion, the horizontal earthquake response of the sliding bearings could be affected by fluctuations in frictional force [1]. Experimental research shows that vertical motions do not affect the earthquake response of sliding seismic isolator in practice. However, few studies have analytically verified the mechanism. The dependence of friction coefficient on the bearing pressure when a bearing is subjected to vertical motion has not been clarified yet.

---

[1] *Department of Civil Engineering Systems, Kyoto University, Yoshida Honmachi, Sakyo-ku, Kyoto, Japan FAX: +81-75-753-5926*
[2] *Department of Civil Engineering Systems, Kyoto University, Yoshida Honmachi, Sakyo-ku, Kyoto, Japan FAX: +81-75-753-5926*
[3] *Department of Civil Engineering Systems, Kyoto University, Yoshida Honmachi, Sakyo-ku, Kyoto, Japan FAX: +81-75-753-5926*
[4] *Kawasaki Heavy Industries, LTD., 1-1, Kawasaki-cho Akashi, Hyogo, Japan FAX: +81-78-913-1366*

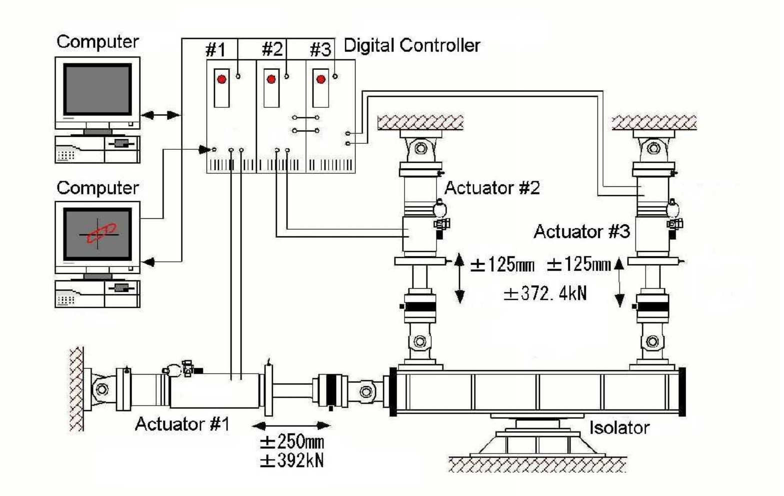

**Figure 1: Outline of test system**

To determine the effect of vertical motions on the earthquake response of sliding seismic isolator, we did static cyclic loading tests, pseudo-dynamic tests, and earthquake response analyses.

## TEST SYSTEM

Figure 1 shows an outline of the test system. It had six subsystems for loading, controlling, analyzing, measuring, and recording. Three actuators used for loading gave horizontal deformation through a horizontal beam to the seismic isolation bearing. The two vertical actuators also produced loads and numerically controlled the horizontal level of the beam.

A sliding seismic isolator was an isolating system including both a sliding and a rubber bearing. Horizontal springs were excluded from the loading tests, as they can numerically be modeled as linear springs. The sliding bearing was scaled down to a 1/4 -scale model and relied on the sliding friction between a Teflon plate and a stainless steel plate. The specimen was designed to have a dead weight of 365.7 kN and bearing pressure of 12.96 MPa.

## STATIC CYCLIC LOADING TEST

### 3.1 Method

Static cyclic loading test was done to study the friction coefficient of a sliding bearing, a type of sliding seismic isolator. The horizontal loading velocity was first increased from 0.2 to 3.5 kine under a constant axial force of 367.5 kN to measure the dependence of friction coefficient on sliding velocity. The bearing pressure was then changed from 4.18 to 15.42 MPa to measure the dependence of friction coefficient on the bearing pressure.

### 3.2 Dependence of Friction Coefficient

Figure 2 shows the measured friction coefficient for different sliding velocities and bearing pressures from the static cyclic loading test. The friction coefficient rapidly increased as the sliding velocity decreased to a certain level, below which it leveled off. When the sliding velocity was sufficiently large, typical of actual seismic waves, the friction coefficient was a constant 0.133, independent of sliding velocity.

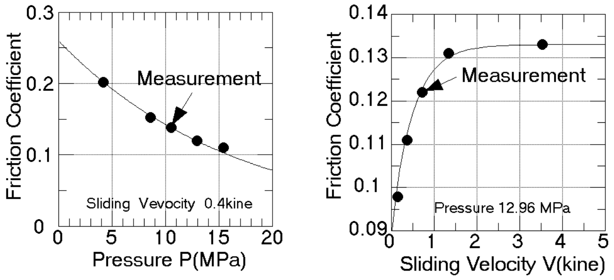

Figure 2: Dependence of friction coefficient on velocity and pressure

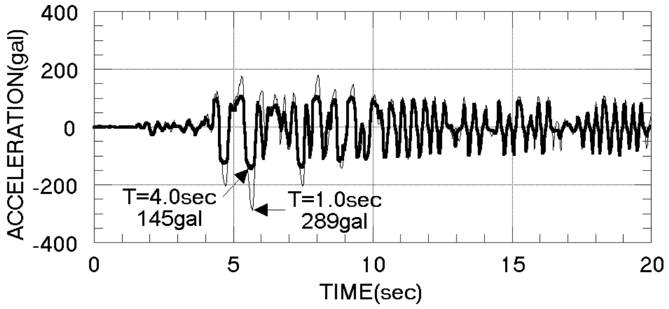

Figure 3: Effect of spring stiffness

In contrast, as the bearing pressure increased, the friction coefficient decreased linearly. Actual earthquakes have vertical motions, so the bearing pressure on the sliding bearing is constantly changing thus causing constant fluctuation in the friction coefficient. Therefore, we investigated the bearing response to a simulated earthquake with vertical motions.

## 4. PSEUDO DYNAMIC TEST

### 4.1 Method

We modeled a design specimen of a five-span continuous steel box girder bridge [2]. The model had one degree of freedom in which a bridge girder was supported by a sliding bearing and a horizontal spring. A seismic acceleration waveform was input into this model. The input wave was scaled from that recorded by The JMA Kobe record of the Hyogo Ken Nanbu Earthquake (hereinafter referred to as KOBE).

Characteristics of the entire seismic isolation system were determined when a simulated earthquake response test was done simultaneously with the test of the numerically modeled horizontal spring. The characteristics of the restoration force of sliding bearing were measured in a loading test. Therefore, it was possible to optimize the secondary stiffness of sliding seismic isolator by changing the stiffness of the numerically modeled horizontal spring.

In the simulation, the input scale of vertical motions and the natural period after the bearing has started to slide were recorded to deduce the parameters below.

*Stiffness of horizontal spring (k=92.5 kN/m, 1,480 kN/m)
Constant axial force 367.5 kN, KOBE-NS 36%
*Input scale of vertical motions (constant axial force, KOBE-UD 150%)
*Stiffness of vertical spring 658 kN/m KOBE-NS 56%
Isolation effect under vertical motions (T=1.0 to 4.0 sec)
KOBE-UD 100%, KOBE-NS 36%

### 4.2 Effect of the Stiffness of Horizontal Spring

Figure 3 shows the time-dependent acceleration response for natural periods (after sliding) of 1.0 sec and 4.0 sec. The natural periods were calculated from the stiffness of the horizontal spring. This figure shows that the response acceleration saturation was affected by sliding. It provided a large isolation effect when the natural period was large after the bearing had started sliding. When this sliding natural period was about 4.0 sec, theinertia acting on the bridge pier was limited to about 130 gal. This value corresponded to the yield acceleration of the bearing.

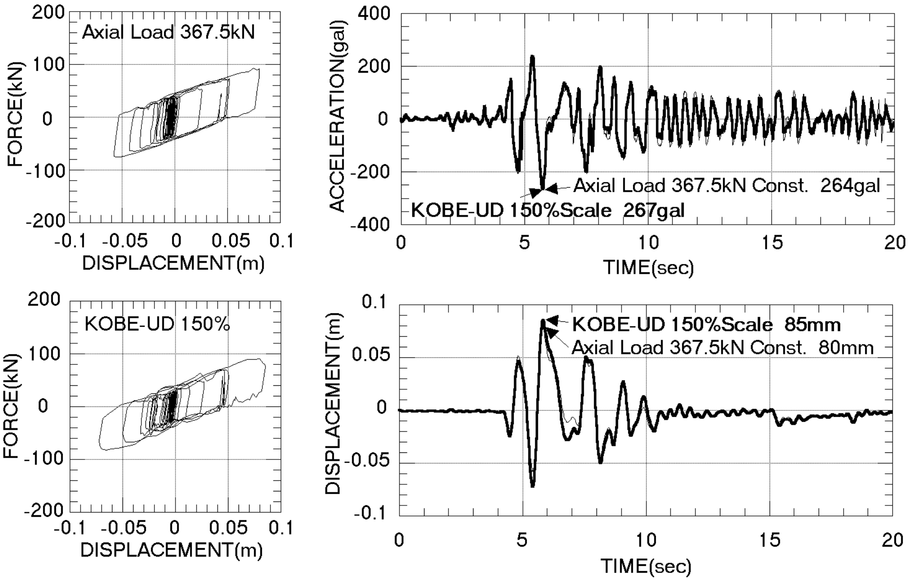

**Figure 4: Effect of the input scale of vertical motions**

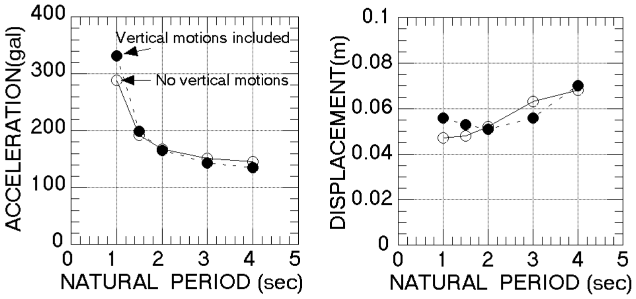

**Figure 5: Isolation effect with vertical motions**

### 4.3 Response to Earthquakes with Vertical Motions

Figure 4 shows the hysteresis curves together with the time-dependent response acceleration and response displacement for the following two cases: constant applied axial force (for horizontal motions only), and applied vertical KOBE-UD 150% motions. Because the vertical motions changed the coefficient of friction, the hysteresis curve under vertical motions was more round than that under a constant axial force. However, both the response acceleration and the displacement were nearly the same as that when vertical motions were neglected. Although vertical motions caused fluctuations in the friction coefficient, they did not affect the horizontal earthquake response.

Figure 5 shows the maximum response acceleration and displacement for different sliding natural periods when the bearing was and was not subjected to vertical motions. Changes in the natural period with the vertical motions had little affect on the seismic isolation effect: the maximum response value was nearly independent of vertical motions. Therefore, the seismic isolation effect and earthquake response of these bearings can be reproduced without including vertical motions.

## ANALYSIS OF THE RESPONSE TO EARTHQUAKES WITH VERTICAL MOTIONS

### 5.1 Method

The analysis model had one degree of freedom with sliding seismic isolator, similar to that for the simulation above. The natural period during sliding, as calculated from the stiffness of the horizontal spring, was set to 4.0 sec (k=92.5 kN/m). The vertical stiffness of the bearing was assumed to be sufficiently high so that a fluctuating

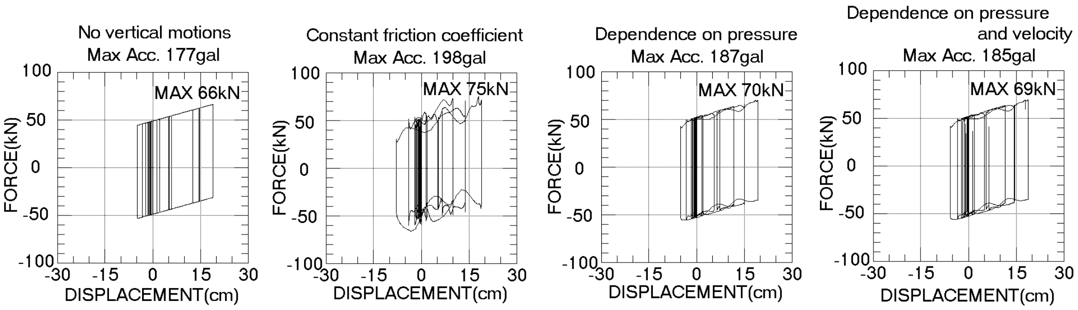

**Figure 6: Earthquake response with vertical motions**

load (mass on the bearing times the vertical acceleration) works on the sliding bearing as an axial force in the vertical direction. The dependence of friction coefficient on the bearing pressure, and sliding velocity (from Fig. 2) were approximated by equations (1), and (2) below.

The dependence of friction coefficient on the sliding velocity [3]:

$$\mu_v = \mu_{\max} - (\mu_{\max} - \mu_{\min})\exp(-av) \bullet\bullet\bullet\bullet\bullet\bullet\bullet\bullet\bullet\bullet\bullet\bullet\bullet\bullet\bullet\bullet\bullet\bullet\bullet\bullet\bullet\bullet\bullet\bullet \qquad (1)$$

$\mu_{\max}$ : Friction coefficient in the high sliding velocity range = 0.133
$\mu_{\min}$ : Friction coefficient in the low sliding velocity range = 0.09
$a$ : Coefficient to regulate the dependence on the sliding velocity = 2
$v$ : Sliding velocity (kine)

The dependence of friction coefficient on the bearing pressure [4]:

$$\mu_p = 0.26\exp(-0.06\sigma_p)$$

(2)

$\sigma_p$ : Bearing pressure (MPa)

The nonlinear model assumed the sliding bearing was rigid plastic with the primary stiffness set to infinity. The friction force was deduced from the relation between velocity and load. When the frictional force was larger than the applied force, the bearings did not slide. We used the Runge-Kutta method at integrating intervals of 0.002 sec and the wave recorded by The JMA Kobe record of the Hyogo Ken Nanbu Earthquake (hereinafter referred to as KOBE) for earthquake input. The analyzing program was drawn up by MATLAB-Simulink [5].

### 5.2 Earthquake Response under Vertical Motions

Figure 6 compares the hysteresis curves of the bearing subjected to KOBE-NS and KOBE-UD with respect to the friction coefficient. As the friction coefficient depends on the vertical fluctuation, the hysteresis profile was complicated when the friction coefficient is kept constant; for instance, the maximum friction force was about 14% larger than that when the bearing was not subjected to vertical motions, while the maximum response acceleration was 12% larger. These values are significantly different from those of the simulation. These test results show that an analysis at a constant friction coefficient cannot reproduce the behavior of the sliding bearing, although the simulation showed that the effect of vertical motions was insignificant for earthquake response.

When the dependence of friction coefficient on the bearing pressure was included, the bearing had a hysteresis profile in good agreement with that without vertical motions, despite the fact that the friction coefficient changes from the vertical motions. The friction coefficient changed from 0.107 to 0.179 due to these motions, but the frictional force (friction coefficient times vertical load) did not change much even with the vertical motions. Both the maximum friction force and the response acceleration were 6% different from those without vertical motions on the bearing. It is appropriate, therefore, to include the dependence of friction coefficient on the bearing pressure for analyzing the earthquake response under vertical motions. This method closely reproduced the behavior of sliding seismic isolator. It was also possible to approximately reproduce earthquake response through analysis without vertical motions, i.e., a constant friction coefficient, as found with conventional methods.

The results of earthquake response analysis were in good agreement between the case where both bearing pressure and sliding velocity dependence were included and the case where only the bearing pressure dependence was included. As shown by analytical research on the sliding velocity dependence on frictionv coefficient [3], the sliding velocity is sufficiently high during actual earthquakes that the sliding velocity dependence of friction coefficient does not affect the earthquake response.

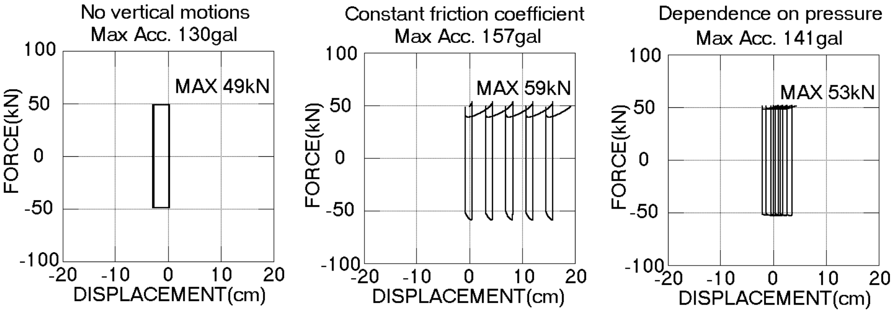

**Figure 7: Response of sliding bearing to sine wave**

### 5.3 Response of Sliding Bearing to Sine Waves

Horizontal and vertical motions in actual seismic waves are never constant. If a large horizontal motion occurs when the friction force is the smallest from fluctuations in vertical motion, the displacement of the sliding bearing will be excessive. Therefore, stationary sine waves were input as seismic waves to study the basic response characteristics when horizontal and vertical motions act on a sliding bearing. The input horizontal and vertical waves were in phase to have peaks at the same time. The amplitude of input acceleration was set at 200 gal, and the period to 1.0Hz for both waves. To understand the response characteristics of a sliding bearing, horizontal springs were neglected in this analysis.

Figure 7 shows the hysteresis curve of the sliding bearing for five seconds of this input sine wave. When the friction coefficient was kept constant, both the response acceleration and displacement were larger when vertical motions were included than when they were absent. As the friction force equals the product of friction coefficient and vertical load, the response was larger with a smaller load if the friction coefficient was not changed.

Conversely, the response was smaller when the dependence of friction coefficient on bearing pressure was included than when the friction coefficient was constant, but increased when vertical motions were included. The response was larger when the bearing pressure was larger because the friction coefficient decreased with bearing pressure. In actual seismic waves, horizontal and vertical motions are random. This test result showed that sliding bearings had larger responses when the peaks of horizontal and vertical motion coincided.

## CONCLUSIONS

Simulated earthquake response tests and earthquake response analyses were done under the effect of vertical motions for sliding seismic isolator subject to vertical motions, and the following conclusions were obtained.

1. The friction coefficient fluctuated according to its dependence on the bearing pressure. But, the fluctuations were small and the vertical motions did not have much effect on the horizontal earthquake response. The earthquake response under vertical motions could approximately be reproduced by the behavior with horizontal motions alone.
2. A large seismic isolation effect was obtained, even under vertical motions, when the stiffness of the vertical spring was sufficiently small.
3. To analyze the earthquake response of sliding seismic isolator under vertical motions, it was difficult to reproduce their actual behaviors when the friction coefficient was constant. For this purpose, it was necessary to include the dependence of friction coefficient on the bearing pressure.
4. The effect of a sliding-velocity-dependent friction coefficient on the earthquake response was insignificant.

5. For oscillating motions, sliding bearings had a large earthquake response when the peaks of the vertical and horizontal motions coincided.

## REFERENCES

[1] Susumu Okamoto. (1995), “Basic research on the effect of vertical motions on dynamic behavior of a bridge with sliding type base isolation system during earthquake”, Proceedings of the 23th JSCE Earthquake Engineering Symposium, Japan Society of Civil Engineers, pp517-520

[2] Public Works Research Center (1992), “Manual for seismic isolation design of road bridges (Draft)” , Ministry of Construction, Government of Japan

[3] Susumu Okamoto, Yasuharu Fukazawa, Shunji Fujii, Daisuke Ozaki (1995), “Dynamic behavior of a bridge with sliding type base isolation system during earthquake”, Journal of structural mechanics and earthquake Engineering, Japan Society of Civil Engineers, No. 513/I-31, pp191-200

[4] Shoji Hayashi, Yosihisa Kitamura, Masaaki Saruta (1998), “Seismic isolation system using rubber bearings and sliding bearings”, The 10th Japan Earthquake Engineering Symposium, pp2807-2812

The Math Works, Inc. (1997): SIMULINK Dynamic System Simulation for MATLAB