Performance Seismic Design of Resilient Sliding Isolation System for Protection of Equipments

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ABSTRACT:

Seismic isolation is one of the effective methods to protect equipments. It helps to control seismic response accelerations in equipment below its allowable level. Among different types of isolation systems, the combination of restoring spring and slider, also called as resilient sliding isolation (RSI) system, is the one which has been effectively used for protection of equipment. Principal design parameters for this type of isolation system are stiffness of spring and friction coefficient of slider. There may be number of combinations of these design parameters which can enable the isolated equipment to remain functional during and after the predicted seismic event. The optimum design of RSI can be considered as the one which maintains the response acceleration in the equipment below its allowable limit and at the same time keeps the relative displacement between floor and the equipment to the minimum. This study deals with optimum design of resilient sliders. First the RSI system is modeled analytically and accuracy of the model is then validated by shaking table tests. The validated model is used to determine optimum design parameters for different levels of allowable accelerations. Results show that the optimum period decreases and the optimum friction coefficient increases with higher allowable acceleration.

Keywords: equipment, seismic isolation, resilient sliding system, optimum design, shaking table.

1. INTRODUCTION

Recently desired performance objective of "operation" or "immediate occupancy" of sensitive equipments has made the engineers to adopt non-conventional method for protection of these systems. Seismic isolation as a reliable and economical method can be recommended to achieve these performance objectives.

This paper focuses on dynamic behaviour and design of isolation systems that comprise of friction slider and restoring spring. First, a numerical model of a raised floor, seismically isolated with friction slider and spring is proposed. Then the model was validated by performing shaking table test. This model was used to predict dynamic behaviour of seismic isolated equipments and to reach at the optimum design of isolation system. For the purpose of this study, design of isolation system is defined as optimum if it results in minimum displacement while maintaining the maximum acceleration below allowable level. Two groups of earthquakes recommended by Transportation Ministry of Japan were considered in this paper.

2. RESILIENT SLIDING ISOLATION (RSI) SYSTEM

Sliding bearing limits the transmission of seismic force to level that is function of friction

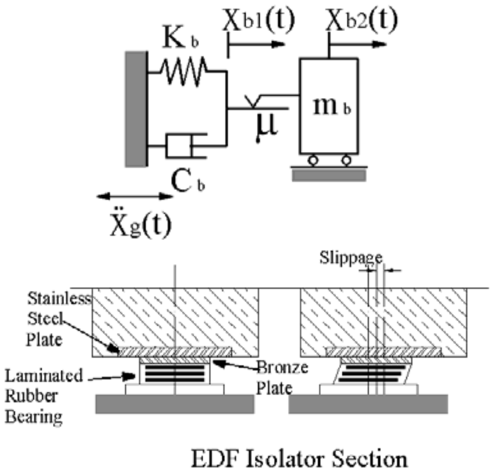


Fig.1 Slider and spring in series

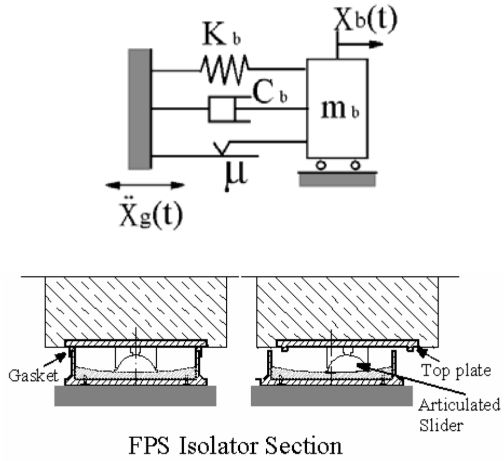


Fig.2 Slider and spring in parallel

coefficient of sliding interface. This behaviour is interesting for protection of non-ductile and non-structural components against earthquake when expected acceleration is more than their strength level. However there are some negative aspects in seismic behavior of sliding bearings like lack of restoring force and transmission of high frequencies [1,2]. Transmission of high frequency excitation causes damage in sensitive equipments.

To avoid these undesirable features, sliding bearings are typically used in combination with a restoring spring. When spring and slider are used in series (Fig1), sliding does not occur for seismic excitation below a certain threshold, and the isolated structure responds only in elastic part [3]. This behavior can filter direct and indirect excitation of high frequency due to stick-slip. However in strong excitation, this system may result in residual displacement.

When spring and slider are in parallel combination i.e. *Resilient Sliding Isolation System* (Fig 2) transmission force to equipment is equal to restoring force of spring plus friction force at sliding interface. This combination can reduce both transmission of indirect high frequency excitation and residual displacement.

3. ANALYTICAL MODELING OF RSI

In numerical model of resilient sliding isolation the essential feature that need to be modeled for behavior of sliding bearing is the velocity dependence of the coefficient of friction and influence of bearing pressure in the coefficient. Although, biaxial interaction and its effect can be considered as another feature of modeling.

Here, velocity dependence of friction coefficient can be modeled by the following equation [4]:

$$\mu = \mu_{max} - \Delta\mu \exp(-\alpha|\dot{U}|) \tag{1}$$

In which, μ_{max} is the maximum value of the coefficient of friction, $\Delta\mu$ is the difference between its maximum and minimum value. Effect of bearing pressure on friction coefficient is accounted by factor α and $\dot{U}$ is the absolute velocity. Biaxial interaction is considered as model proposed by Park and Wen [5]. In addition to friction element, laminated rubber bearings are assumed as a linear spring and frames is considered as elastic beam element. Mass of frame elements and blocks deemed as lumped mass element that have degree of freedom in horizontal direction (X-Y) and rotation about vertical axis (θ).

4. VERIFICATION OF ANALYTICAL MODEL

Experimental Test

In order to establish the reliability of numerical model for the isolation system used in the study a series of shaking table were performed at Disaster Prevention Research Institute of Kyoto University. This shaking table system can reproduce acceleration of 1.0g in three direction with maximum stroke of 0.3m in horizontal and 0.2m in vertical direction.

In this experiment a 4.15 m x 2.65 m raised steel floor, supported on four frictional sliders at the corner and two laminated-rubber bearings was considered (Fig 3 and 4). The total weight of this raised floor was 100 KN. Rubber bearings have a square plan of 250 mm x 250 mm with three different thicknesses. Modulus of elasticity of rubber is 1.2 KN/mm^2. The bearings were designed for periods of 1.1, 1.75 and 3.0 seconds respectively. Sinusoidal tests on sliding bearings before shaking table test showed that the minimum and maximum values of friction coefficient are 0.05 and 0.15 respectively.

The system was tested using two groups of earthquakes, recommended by Transportation Ministry of Japan. These groups are T1 (offshore) and T2 (inland) and each one contain 9 records. Each group, based on soil condition of recording station further divided into three categories, records on stiff soil (soil typeI), medium soil (soil type II) and soft soil (soil type III). Almost 70 runs were made with different isolators and earthquakes. Displacement, acceleration, vertical pressure on bearing and lateral force of system were measured during these tests.

The response of system recorded in experiment and computed by numerical model, which was compared for different design parameters of earthquake motions. Shear force of system under earthquake recorded on soil type I is shown in Fig.5a when period of spring is 1.1 second. In Fig.5b lateral relative displacement of raised floor recorded at soil type II is illustrated when period of spring is 1.75 second. These figures shows relation of results obtained from numerical model for different conditions.

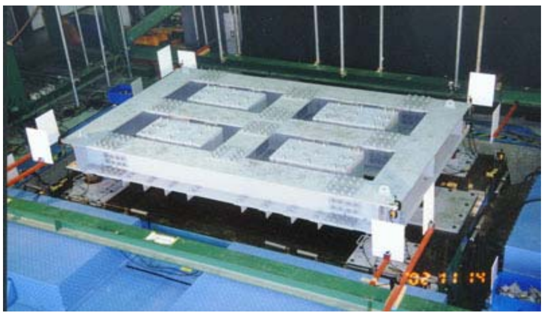


Fig.3 Experimental Setup

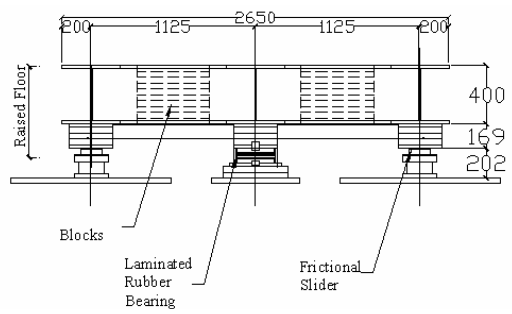
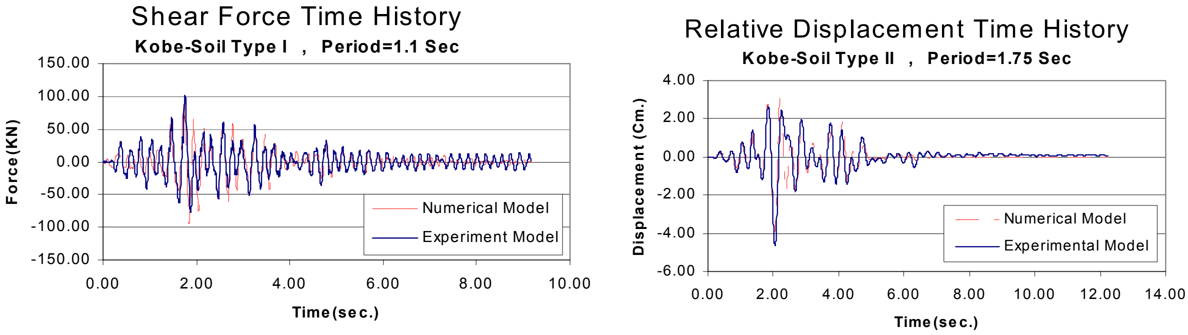


Fig.4 Details of Test Setup



(a) (b)

Fig.5 Comparison of Response of Experimental and Numerical Model

5. DESIGN METHODOLOGY

Dynamic characteristics of equipments like stiffness or damping may effect on any decision about modeling and design methodology of their isolation systems. In this regard, Almazan et al. [6] compared response parameters of a rigid block and flexible superstructure (period 0.5 sec.) were isolated by FPS isolator. Their result show that difference between the isolator deformation computed from both models is very small; however slightly larger discrepancies (about 10 percent) was observed in shear force. Though most of equipments have solid components, flexibility of equipment if there, do not have considerable effects on response of their isolation system. Thus in isolated equipment, response of seismic isolation system can be obtained with acceptable accuracy by assuming "equipments + raised floor" as a rigid mass. Determination of stiffness and friction coefficient of SDOF model based on seismic performance objective of equipments is purpose of design methodology in this part.

Since seismic performance objective of equipments is qualitative term (operation during or immediately after earthquake) it should be quantified by limiting values of measurable response parameters for practical design. For example in structures, this measurable response parameter is "story drift" and it is limited to 2%~3% when level of performance is Life Safety. In equipments and nonstructural elements, because of their rigid behaviour, performance objective is defined by "limiting response acceleration" or "lateral force". For nonstructural components above the isolation interface, provisions and codes of seismic isolated structures [7] recommends that they shall "resist the *total lateral seismic force* equal to the maximum dynamic response of element or component". In other words, if due to any reason nonstructural components cannot resist more than specific level of lateral seismic force, isolation system should design to control maximum lateral seismic force to less than or equal to level of resistance of equipment.

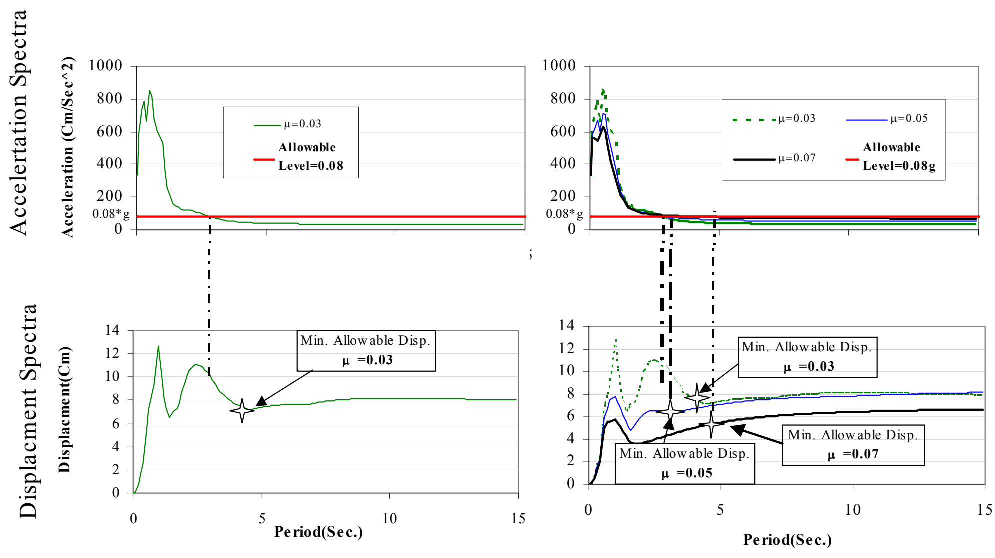
Table 1 indicates suggested peak accelerations by manufacturer for some models of disk drives in computer systems. The response acceleration if exceeds this value may cause permanent damage and loss of readable data [8]. In this table, for operating and non-operating condition of different disk drives maximum seismic bearable acceleration varies between 0.2g-1.0g. These values in practice are reduced by safety factors to *Maximum Allowable Acceleration*. For protecting these systems during earthquakes, stiffness of spring and friction coefficient of slider should be selected to limit horizontal input acceleration under their allowable values.

Table 1 Maximum seismic resistant acceleration on disk drives [8]

Manufacturer's Model #	Max. g / Operating	Max. g / Non-Operating
DEC - Alpha Server - #8200	0.5 g	0.5 g – 1.0 g
SUN - Class III Drive	0.25 g	1.0 g
DEC - RZ 28 Drive Unit	0.5 g	0.5 g
HP - Model 20 Drive Unit	0.25g	N / A
HP - Enterprise 9000	0.2g-0.5 g	0.5 g – 1.0 g

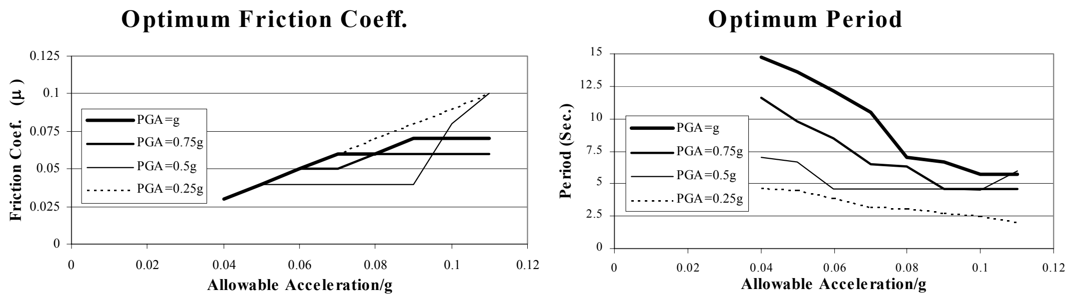
Optimum Design Procedure

Any combination of stiffness and friction coefficient of resilient sliding isolation, which control response acceleration under allowable level of acceleration, can be accepted as eligible design parameters for protecting equipment in earthquake. But most of equipments have connections with other systems like power, water supply or main server and safety of connections to these systems is essential to ensure the functioning of equipment during earthquake. Therefore beside safety of equipments, designer should control displacement of isolated equipments in earthquake to minimum value. In this regard, determination of stiffness and friction coefficient of isolators to control input acceleration under allowable level and to minimize lateral displacement is the optimum design of resilient sliding isolation.Fig.6 clearly depicts procedure of optimum parameter recognition for specific allowable acceleration. Maximum response acceleration and displacement spectra of SDOF model of isolated equipment under El Centro earthquake is shown in Fig6-a for isolation system with friction coefficient of 0.03. In this figure allowable acceleration of equipment is assumed as 0.08g. Safety of equipment can be guaranteed when



(a) **(b)**

Fig.6 Procedure of Optimum Parameter Recognition for El Centro Earthquake



(a) **(b)**

Fig.7 Optimum Parameter of Resilient Sliding Isolation for El Centro Earthquake

maximum acceleration of its isolated model is equal or less than this level of acceleration. Safety region begins from crossing point of dashed-line with response spectra. Isolation systems with period longer than this point are eligible to ensure operation of equipment during or immediately after El Centro earthquake. Among these eligible periods just one of them has minimum displacement that is shown in displacement spectra with *star symbol*.

This procedure is repeated for different values of friction coefficient in Fig 6-b. Crossing point of dashed lines with each spectra show start point of their eligible range for allowable acceleration 0.08g. Period at these points for three coefficient friction μ=0.03,0.05,0.07 are T_i=2.9,3.0,4.6 seconds. For periods more than T_i , minimum displacement of each friction coefficient has been highlighted with star *symbol*. Among three highlighted points, displacement of one of them with friction coefficient 0.07 and period 4.6 seconds has minimum value. Between three friction coefficients for allowable acceleration 0.08g this point introduce property of an isolator that can protect equipment under El Centro earthquake with minimum displacement. By using this procedure for range of friction coefficients, optimum parameters of resilient sliding isolator can be determined for allowable acceleration 0.08g or other values of allowable acceleration.

In Fig.7 optimum parameters of resilient sliding isolator for different allowable accelerations of this isolator were computed for feasible range of friction coefficient between (0.03~0.10) and periods between (0~15sec.). These parameters were computed by using cited procedure for any allowable level of acceleration between (0.04g-0.11g). Input earthquake was scaled to 0.25g, 0.5g, 0.75g and 1.0g to evaluate the effect of Peak Ground Acceleration (PGA) on optimum parameters. Fig.7-a illustrates, optimum friction coefficient has ascending trend with increasing of allowable level of acceleration but different values of peak ground acceleration have not clear effect on optimum value of this parameter. Optimum period in Fig.7-b has descending variation with increase of allowable acceleration. In this figure optimum period of isolation system under higher level of peak ground acceleration of earthquake is longer.

6. EVALUATION OF OPTIMUM PARAMETERS

To determine variation of optimum parameters of resilient sliding isolators under several earthquakes gives an evaluation about optimum design of these isolators based on seismic performance objective of equipments. In this part, optimum parameters of resilient sliding isolators are obtained analytically for T1 (offshore) groups of motions. In order to have proper

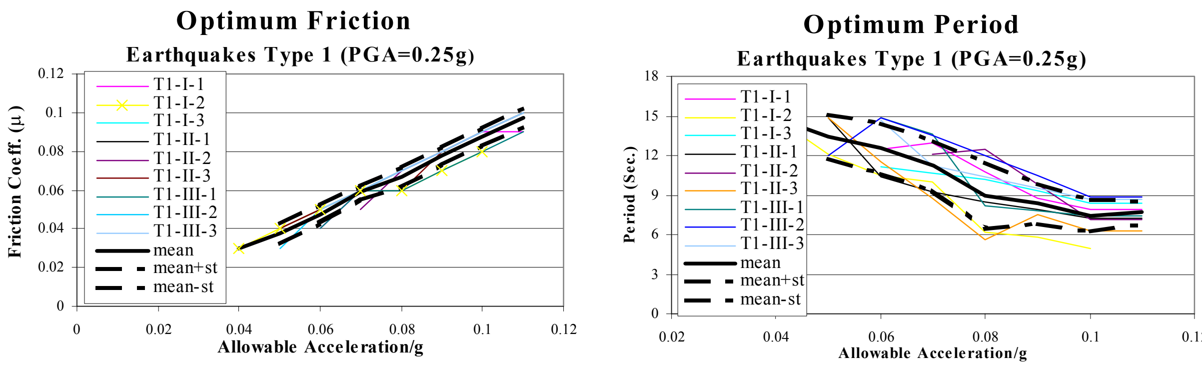


Fig.8 Optimum Friction and Period of Resilient Sliding Isolation System under records of T1

comparison all earthquakes are scaled to site specific Peak Ground Acceleration (PGA) equal 0.25g (Moderate seismic zone) and 0.5g (High seismic zone)[9].

Fig.8 shows optimum parameters of resilient sliding isolators under records of T1 that were scaled to 0.25g. In this figure earthquakes recorded on stiff, medium and soft soil are scripted with T1-I, T1-II and T1-III. Variation of optimum period and friction coefficient with allowable level of acceleration has same trend with variation of these parameters in El Centro earthquake. For design purposes Mean and, "Mean ± Standard deviation" of optimum values for all earthquakes show that optimum frictions are almost in the same line for all earthquakes in T1 while optimum period can be selected from a band of period for any allowable acceleration of equipments.

Comparison between mean values of optimum parameters under records of T1 and T2 and their Standard deviation is shown in Fig 9. In this figure mean values of optimum friction coefficient for two types of earthquakes are nearly same and have linear variation with increasing of allowable level of acceleration. But it can be seen that the difference between mean values of optimum period in two types of earthquakes is around 2 seconds and both have descending variation by increasing allowable level of acceleration. For these earthquakes that scaled to PGA=0.25g, optimum parameter selected among range of friction coefficient between (0.03~0.10) and period between (0~15sec.) and computed for equipments that their allowable level of acceleration varies between (0.04g-0.11g).

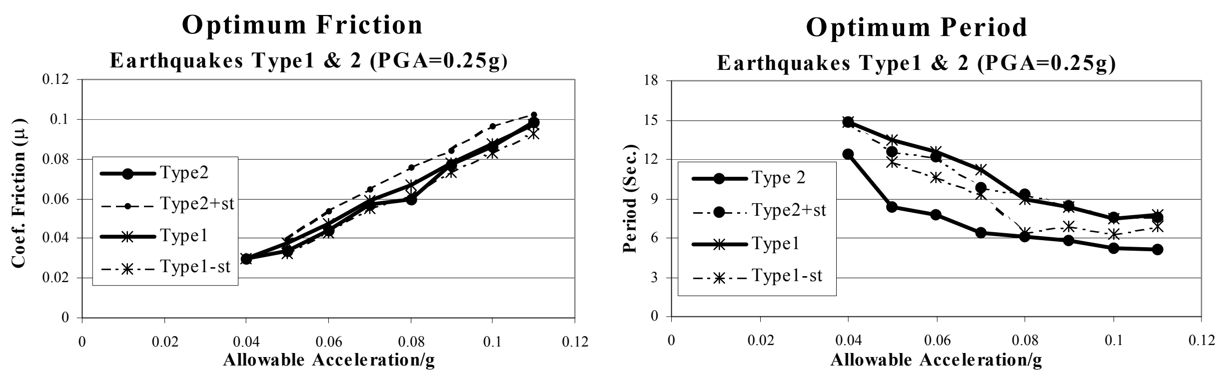


Fig.9 Optimum Friction and Period of Resilient Sliding Isolation under records of T1 &T2

7. CONCLUSIONS

The paper discusses the evaluation of design parameters of the Resilient Sliding Isolation system to achieve performance objective of equipments. Analytical method based on single degree of freedom is proposed to obtain these parameters. In addition the design parameters obtained by this method also lead minimum relative displacement. The accuracy of the method is validated by shaking table test of raised floor isolated by resilient sliders. Optimum design parameters of these resilient sliding systems subjected to two type of Japan standard earthquakes are obtained for different values of allowable level of acceleration for the equipments. Results of analysis show:

1. For higher values of peak ground acceleration of earthquake, optimum period of resilient sliding isolation is longer.
2. Optimum friction coefficient of isolation system under earthquakes T1 and T2 in moderate seismic zone has almost linear relation with increasing level of allowable acceleration.
3. Optimum period of isolation system under earthquakes T1 and T2 in moderate seismic zone becomes shorter when allowable level of acceleration increases.
4. In high seismic zone, standard deviation of optimum parameters is larger than moderate seismic zone. Mean of optimum parameters in high seismic zone has same trend of variation with moderate seismic zones.

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