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Viability of Slab Sliding System for Single Story Structure

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Abstract**—**Slab sliding system (SSS) with Coulomb friction interface between slab and supporting frame is a passive structural vibration control technology. The system can significantly reduce the slab acceleration and accompanied lateral force of the frame. At the same time it is expected to cause the slab displacement magnification by sliding movement. To obtain the general comprehensive seismic response of a single story structure, inelastic response spectra were computed for a large ensemble of ground motions and a practical range of structural periods and friction coefficient values. It was shown that long period structures have no trade-off relation between force reduction and displacement magnification with respect to elastic response, unlike short period structures. For structures with the majority of mass in the slab, the displacement magnification value can be predicted according to simple inelastic displacement relation for inelastically responding SDOF structures because the system behaves elastically to a SDOF structure.

Keywords**—**Earthquake, Isolation, Slab, Sliding.

I. INTRODUCTION

COULOMB friction damping is one of the vibration isolation and response reduction technologies. Base isolation system with Coulomb friction sliding interface between superstructure and foundation is the most popular and common application of this passive structural vibration control method. Slab sliding with Coulomb friction interface between slab and supporting frame is an alternative arrangement of Coulomb friction damping. The slab sliding system can considerably reduce the slab accelerations and the frame forces in the same way as the base isolation system. That might lead to a cost cutback for the frame. Once sliding occurred for base sliding structures, it may be difficult to bring the superstructure back to its original position. This problem might be mitigated by the slab sliding system.

Although residual displacements in hysteretic energy dissipation systems are permanent, for the structure which remains elastic, the sliding displacements are recoverable. In other words the slab can be returned to its initial position after the sliding. It is easy for the supporting frame to maintain elastic after events according to limited force by sliding movement. That means overall structural components could be available for use after earthquake excitations. Unlike ordinary tuned mass damper system, the slab sliding system can avoid excessive redundant mass that is rarely used and a rise in construction cost especially for foundation. Furthermore reduced slab accelerations can contribute to avoid overturning and sliding movement of contents of buildings. That means enhancement of human safety and protection of property in the event of a major earthquake occurrence.

Malushte and Singh have evaluated the seismic response of simple one degree-of-freedom structures with sliding interfaces of Coulomb friction between the top slab and supporting frame and between the base and foundation [1]. Comparison between slab sliding and hysteretic systems has been also conducted in response spectrum form. In the sliding system, the hysteresis loop is rectangular in shape with the force plotted against sliding displacement and in a bilinear hysteretic system the loop is parallelogram with the force plotted against the inelastic displacement of the oscillator. It has been shown that in general, the spectrum for the slab sliding system is lower than the spectra for the bilinear hysteretic system because a bilinear hysteretic system has a post-yielding stiffness in a positive value. It was noted that the slab sliding system is more effective in bringing about a reduction in the slab acceleration and lateral deformation of the frame than the base isolation for the same value of coulomb friction. Some simple ideas for estimating the maximum sliding displacement were attempted [2]. The use of Coulomb friction damping has been also studied for multistory structures with single as well as multiple-sliding interfaces by Malushte and Singh [3]. Numerical results for three three-story structures with different frequencies subjected to three different ground motions have been obtained and discussed. It was shown that any desired level of reduction in slab accelerations or frame deformations can be achieved by a proper selection of the friction coefficient values at different interfaces. A simple calculation method of required friction coefficient values was presented. Additionally they have investigated slab sliding system with a spring for the one degree-of-freedom structures to introduce a recovery mechanism for the purpose of reduction of the slab sliding displacement, but this increases the force on the structure [4].

The slab sliding system has been applied to an actual existing high-rise building located in Tokyo already [5]. The Japanese complex building has 14 floors above ground. The slab sliding system was implemented in the building by disconnecting four of the upper floor slabs from the main structure. Rigorous structural analyses were conducted to validate that the sliding system as a tuned mass damper. The numerical results showed that the slab sliding system could reduce seismic forces in the structure by up to 35% under a large scale earthquake loading

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[6].

Japanese researchers conducted analyses of a series of floor isolation systems with sliding interfaces between the floor and the supporting slab to evaluate the advantages for specific buildings was investigated by conducting three dimensional dynamic tests and time history analyses [7]-[10].

It may be seen from the above discussion that study were conducted for specific buildings with a limited number of ground motions. In order to generalize the findings, it may be seen that there is a need to conduct analysis of a wide range of structures with a large number of ground motions.

The scope of the work described in this paper is to address this need for single story structure with the mass concentrated in the slab by seeking answers to the following questions:

1) *What is the trade-off between frame strength and slab displacement for different frame stiffness?*
2) *How can displacements/demands be predicted?*

Inelastic spectral analyses of the slab sliding system of single story structures are conducted for a large ensemble of ground motions of specific return period probability and a practical range of values of Coulomb friction coefficient in order to obtain general conclusive results concerning seismic behavior of the slab sliding system. Lower values of friction coefficient could provide smaller response accelerations and cause larger maximum sliding displacements. The analytical results are used to consider its inelastic seismic response including trade-off relation between acceleration reduction and displacement magnification as well as the value of Coulomb friction coefficient.

II. Analytical Procedure

A two-degree-of-freedom (2DOF) system shown in Fig. 1 is employed to represent seismic response of a single story structure with the slab sliding system. Two springs are used to simulate behavior of the flame and interface between the slab and the top of the frame. The spring connected to the slab has a 100 times stiffness of another connected to the ground, and elastic perfectly plastic hysteretic characteristic in order to express the Coulomb friction interface, while another spring perfectly elastic. No P-Δ effects in the structure are considered in these preliminary analyses and mass of upper portion of the frame is also ignored. Slab sliding occurs at the interface whenever the lateral force applied to the slab reaches its sliding force determined by the value of coefficient of Coulomb friction μ_f. During sliding, the interface force is friction force. The system has two degree of freedom. However, since mass is applied only in one position this system is the same as a single-degree-of-freedom (SDOF) system. The system can provide explicitly displacement of the top of the frame and sliding displacement, so it was used in this study.

A practical range of Coulomb friction coefficients, μ_f, from 0.1 to 0.5, was considered as well as non-sliding structure (i.e. μ_f is very large). The software framework OpenSees [11] was used to perform the numerical analyses. The integration is performed with a time step of 0.01 s during the earthquake ground motion durations. A value of 5 % critical was applied to the supporting frame. The earthquake records utilized in the analyses were the 20 SAC suite ground motion records which have an exceedence probability of 10 % in 50 years in LA [12].

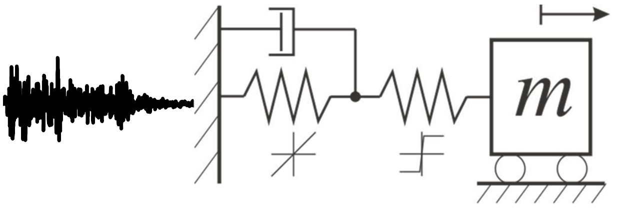


Fig. 1 Model of slab sliding system

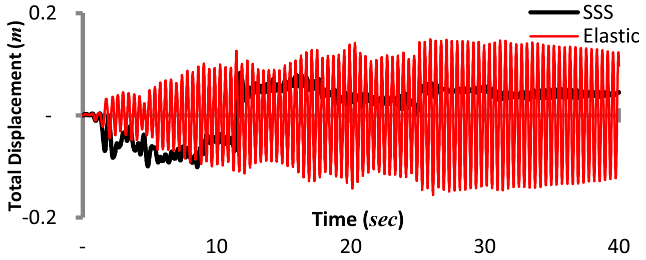
III. Analytical Results

Fig. 2 displays the time history response of the slab sliding system with natural period T = 0.4s and the coefficient of friction value of $\mu_f = 0.2$ as well as linear elastic system with same period for LA01 ground motion [12]. The elastic system displacement relative to the ground gradually increased in amplitude even after the peak absolute acceleration of ground motion at around 12s as shown in Fig. 2 (a). Its resultant peak response displacement was observed at around 26s. The slab sliding system had a peak total displacement of the slab relative to the ground at around 9s which is prior to the occurrence of the peak ground acceleration. The slab sliding system showed little cumulative effect of oscillation because of limited resonance resulting from the slab sliding action. Fig. 2 (b) illustrates a time history of sliding displacement of the slab with respect to the top of the frame. It is evident that the sliding movement is similar to the total displacement of the slab. This is because frame displacements are small. This can also be seen in Fig. 2 (c) where the slab sliding system frame forces are much less than these of the elastic system.

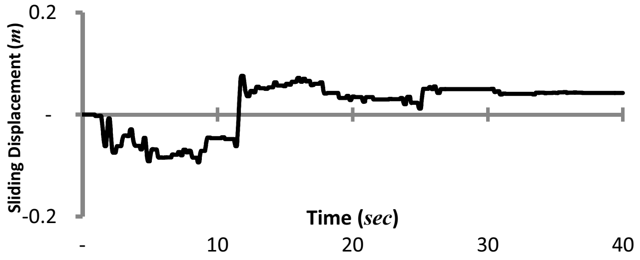
Fig. 3 provides several inelastic response spectra of the slab sliding system with value of the friction coefficient $\mu_f = 0.2$ for an ensemble of 20 SAC ground motions and their median spectra (designated by the darkest lines). The total displacements in the long period range can relatively vary widely with respect to the short period range as shown in Fig. 3 (a). Fig. 3 (b) indicates the absolute acceleration response spectra are governed by the value of coefficient of Coulomb friction in a range of period equal to 2 s or less. Needless to say, all the response accelerations are limited by the friction force of the interface of slab and frame.

Fig. 4 gives median inelastic response spectra for an ensemble of 20 SAC ground motions of the slab sliding system as well as median elastic spectra. In the high frequency range, the total displacements are greater for slab sliding system with smaller values of coefficient of Coulomb friction. While in the low frequency range, smaller coefficient values have smaller displacements with greater reduction of lateral force. When the period is equal to or greater than 1.2s the displacements of slab sliding system must not exceed the linear spectral response, nevertheless the absolute accelerations could be considerably reduced by sliding of slab. As the period increases, the sliding is getting unlikely to occur. Then the displacement and acceleration spectra could approximate the elastic response.

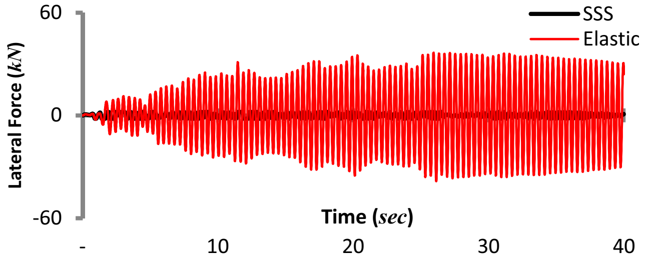
Fig. 5 represents sliding displacement spectra median for an ensemble of the 20 ground motions. For short periods, $T \leq 1$, each value of friction coefficient has same behavior that sliding displacements are larger for longer periods. Sliding doesn't increase significantly after $T \approx 1$. At long periods, sliding is zero because sliding acceleration is not reached. As one would expect, trade-off relationships between the value of friction coefficient and the sliding displacement can be seen in. As for several coefficients of friction value except 0.1, maximum sliding displacements can be observed at $T \approx 1$. A range of period from 2.7 to 3.0 sec has approximately a peak sliding displacement for the smallest value of coefficient $\mu_f = 0.1$. The sliding displacement must be designed to accommodate in the structure to avoid obstacle for slab movement.



(a) Total displacement

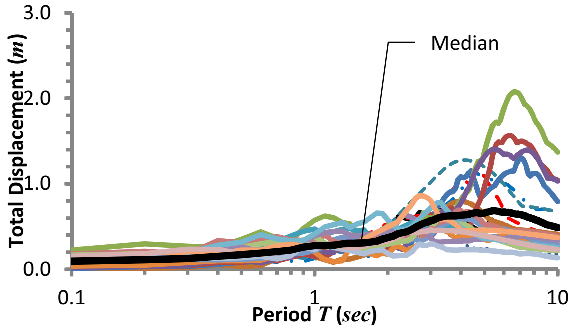


(b) Sliding displacement

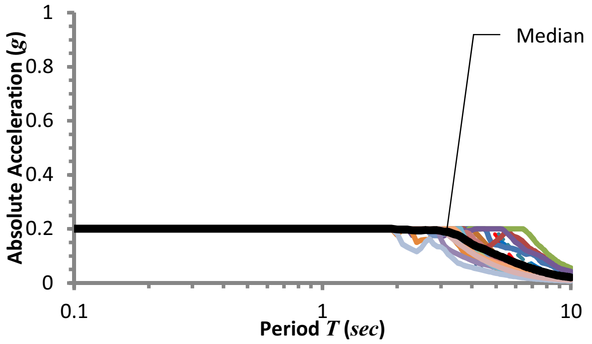


(c) Lateral force

Fig. 2 Time history response ($T = 0.4$ *sec*, $\mu_f = 0.2$, LA01)

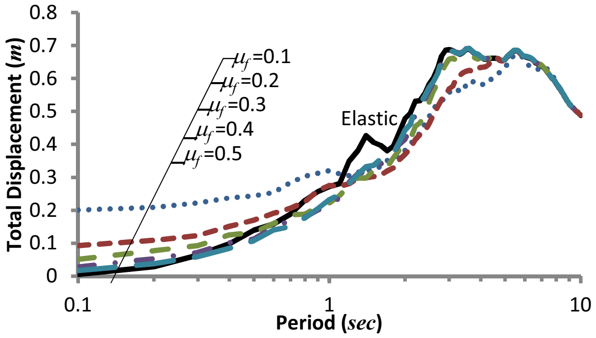


(a) Total displacement

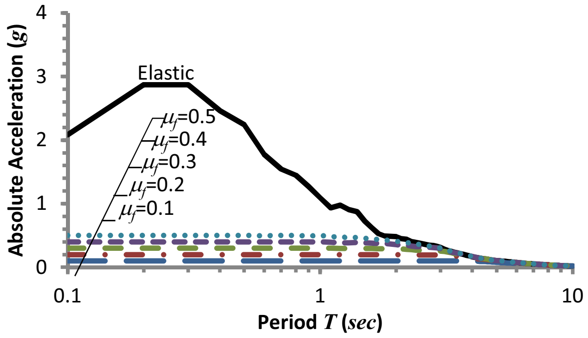


(b) Absolute acceleration

Fig. 3 Response spectra ($\mu_f = 0.2$)



(a) Total displacement



(b) Absolute acceleration

Fig. 4 Median response spectra

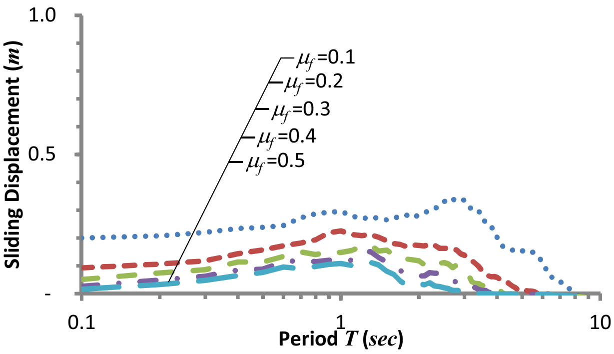


Fig. 5 Sliding displacement

IV. Normalized Response

Fig. 6 shows displacement magnification factors which are normalized displacements with respect to the elastic response displacement. As periods increase the factors diminish and reach 1.0 for all values of friction coefficient. When the period is longer than 1.0 s, the displacement magnification factors are almost 1.0 regardless of the value of coefficient. For example the coefficient value $\mu_f = 0.2$ in a range of the period T equal to or greater than 0.8 s, the magnification factors remain as much as 1.0 while the case $\mu_f = 0.5$ at $T \geq 0.3$ s. Minimum periods capable of remaining the factor no more than 1.0 depend on the coefficient of friction value. Decreasing the value of coefficient causes longer period which can reach 1.0 of the magnification factor.

Sliding action can exceptionally reduce lateral force applied to the frame and absolute acceleration generated to the slab as described above. The value of coefficient of Coulomb friction determines the slab and frame interface force during the sliding phase. Lateral force reduction factor shown in Fig. 7 is defined as an inverse of normalized force with respect to the linear response. The factors equal absolute acceleration ratios of the elastic system to the slab sliding system. Reduction of the absolute acceleration can contribute to prevention of overturning and sliding of the contents inside buildings. Obviously lower coefficient of friction cause greater reduction of the lateral force whenever sliding occurred over the range of periods. In a range of period from 0.2 to 0.3s maximum reduction could be obtained for each value of friction coefficient. As the periods increase from 0.3s the reduction factors decrease.

The Displacement magnification factor and the force reduction factor relationships for each period indicated in Fig. 8 are almost proportional over the values of friction coefficient. Their ratios are higher for smaller periods regardless of the coefficient of friction value. As the period increase the displacement magnification factor decreases for each lateral force reduction factor. It is apparent from observation that the slab sliding system in the long period range can reduce the lateral force without additional displacement to the elastic response displacement.

The total displacement magnification factor for the slab sliding system can be predicted as follows. In a range of the period equal to or less than 0.7s, the *equal-energy principle* (EEP) can provide the following (1) [13]. Symbols used in this equation Δ_t, Δ_e and μ designate inelastic displacement, elastic response displacement and ductility respectively.

$$\frac{\Delta_t}{\Delta_e} = \frac{\mu}{\sqrt{2\mu - 1}} \tag{1}$$

The ductility μ in the equation above could be predicted for the range of the periods as follows [13]. The equation was proposed in order to represent the relationship for short period structures up to 0.7s, based on an assumption that force reduction value R could depend on natural period T. It is just interpolation between very short and long periods (say $0<T<0.7$) in order to solve the problems of the discontinuity between the *equal-displacement principle* (EDP) and the *equal-acceleration principle* (EAP). Therefore it can enjoy no theoretical support as well as EDP.

$$\mu = 1 + (R-1)\frac{0.7}{T} \tag{2}$$

Substitute (2) for μ in (1), a predictable equation below can be derived. For long period structures (say T>0.7), the displacement magnification values are well known to be almost 1.0. The behavior is referred to the equal-displacement principle.

$$\frac{\Delta_t}{\Delta_e} = \frac{1+(R-1)\frac{0.7}{T}}{\sqrt{1+2(R-1)\frac{0.7}{T}}} \tag{3}$$

The computed values by (3) may not be viewed as close representations of the analytical results as shown in Fig. 9. However the equation above can provide conservative estimate except the period of 0.1 of a second. The equal-energy principle could not be employed in such very short period range (say $T \leq 0.1$s) which is available for the equal-acceleration principle. Since proposed (3) is compared with response spectra median for only 20 ground motions, further verification with a wide range of earthquake excitations is needed in order to confirm validity of the equation.

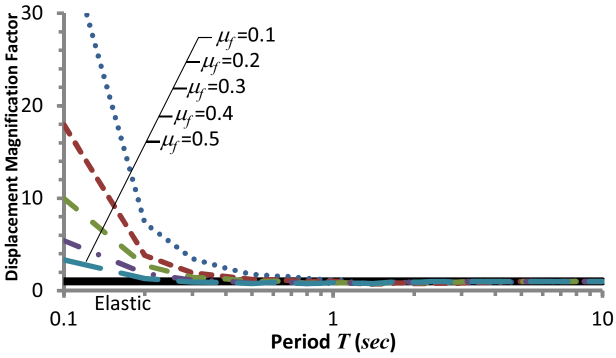


Fig. 6 Displacement magnification factor

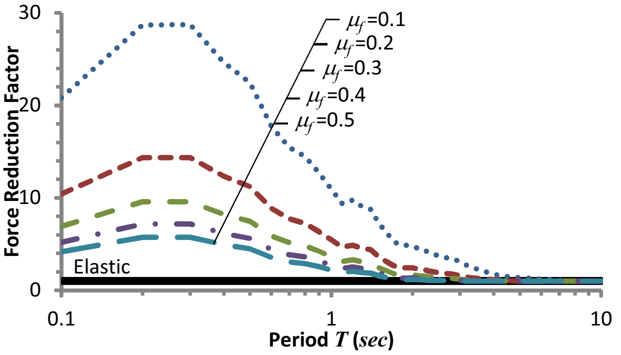


Fig. 7 Force reduction factor

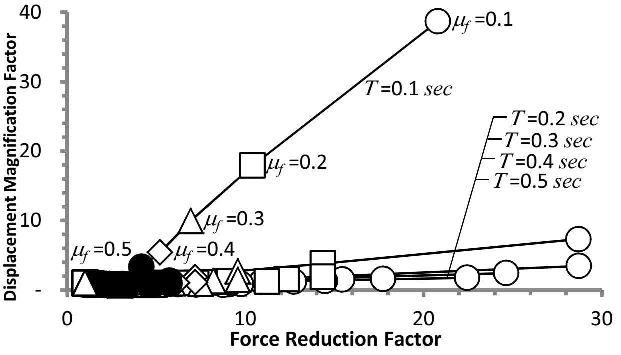


Fig. 8 Magnification and reduction factors relationships

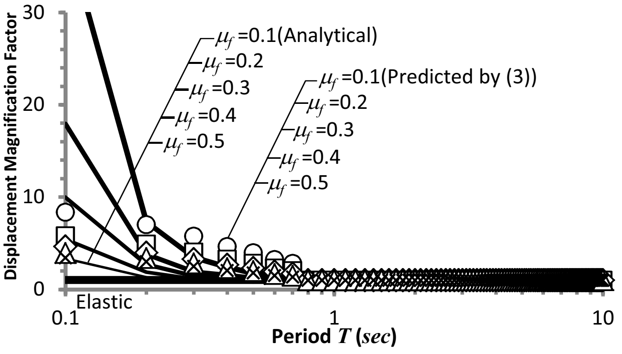


Fig. 9 Prediction of displacement magnification

V. CONCLUDING REMARKS

Inelastic response spectra for a large ensemble of ground motions and a practical range of the friction coefficient values revealed the general comprehensive seismic response of single story structure of the slab sliding system. The results and conclusions of the analytical studies presented in this paper may be summarized as follows:

1) *It is found that long period structures have no trade-off relation between the frame force and the total displacement, unlike short period structures. Smaller values of friction coefficient in the low frequency range have smaller displacements with greater reduction of lateral force.*
2) *The displacement magnification factor with respect to elastic response in the analytical results can be predicted conservatively and roughly by a conventional method except very high frequency structures with the period $T \leq 0.1$ s.*

Investigation into multi story structure of the slab sliding system will be needed as well as consideration of P-Δ effects in order to obtain the general comprehensive seismic response furthermore. A study of sensitivity of mass ratio between the slab and the frame to seismic response of the slab sliding system could be also recommended as a further investigation.

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