A PRACTICAL PROPOSAL FOR SEISMIC ISOLATION DESIGN AGAINST EXTREMELY STRONG EARTHQUAKES

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SUMMARY

The main objective of this paper is to evaluate the applicability of an innovative seismic isolation system (called SPI) form perspective views of any further advantages to other existing systems, its effectiveness against various types of earthquakes through energy analysis, and its cost-effective performance. For this purpose, results of a multi-purpose experimental model has been examined. The model originally was designed to be adjusted for conducting various periods of isolator and yield strength of lead damper. Several number of recorded accelerograms including those of near-field strong ground motions with peak velocities as high as 130 cm/sec are used and compared with the 1940 El Centro and the 1985 Mexico-City earthquakes. To have better interpretation of dynamic behavior, energy analysis based on DRAIN-2DX modules for those experimental results has been developed. In this simulation modeling, properties of all elements including framed super-structure, isolation system and lead dampers were defined based on experimentally verified values so that with identical input earthquake excitation, similar output as of recorded signals could be achieved. On the basis of this analysis, energy time-histories including the damping, the structural and the kinetic energies were separately calculated. These energy quantities are found out to be very supportive of the specific reasons that are inconsistent with actual observation.

Results of a case study for 5, 10 and 20 story moment resistant frame buildings show that utilization of the SPI system is economically comparable with conventional design, while providing the required level of safety. The design procedure indicates that this new system can be practically implemented as suspension tool at roof levels providing longer periods depending on suspension pendulum and yield strength of lead damper. This system is able to accommodate large ground displacement of near-source pulse waves. It is also important to note that the stability of SPI system at its ultimate capacity is fully guaranteed. It is anticipated that results achieved in this research could be put in practice and serve as a design technique since it incorporates a multi-parameter for design variables

INTRODUCTION

Following the two disastrous events of the 1994 Northridge and the 1995 Hyogoken-Nanbu earthquakes, researchers including structural engineers around the world have been working more vigorously to develop highly efficient design methods. The target obviously is to have any type of structures that are capable of withstanding full impact of the site-specific earthquakes including near-source large pulses.

To approach such target within feasibly applicable alternatives, base isolation systems have attracted more attention in recent decades. Lead Rubber Bearing (LRB) and Friction-Pendulum System (FPS) are two leading techniques along with variety of damper devices that have been implemented in many structures [8,12,16 &19].

In spite of providing an acceptable level of safety [11,17], many professional designers are still reluctant to apply these protective systems widely, perhaps due to economical concern as well as several other incertitude factors.

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For instance, though Japan is enjoying the highest contribution in the world's base-isolated structures, total number of isolated buildings may not exceed 700 units, as of early 1999's database [15].

Considering more cost-effective and safety assessment, a proposal based on the suspension methodology has been developed recently. It is called Suspended Pendulum Isolation (SPI) system and can be enhanced by any energy absorbing system, i.e. namely lead and viscous dampers [1]. Fundamental studies indicate that force-displacement characteristic of SPI associated with lead damper is very similar to LRB system [3]. This fact appears to be correct theoretically merely, while its governing forces are acting on the basis of simple pendulum. Indeed, it has been designed as a way to take privileges of both the LRB and FPS techniques, and thus to eliminate limitations of those systems, currently being used in practice.

It is believed that this new system can be practically adopted for seismic isolation of variety of building structures having even more than thirty stories. Evidently, there are very few applications of the suspension type or using the SPI system in building structures for seismic isolation purpose. Suspension-cable bridges [14] and suspended roofs covering giant buildings [9], however, are unique utilization of conventional types since long time ago.

A 30-story twin building, which belongs to the Italian National Electric Board (ENEL) in Naples, Italy, is constructed very recently, has been designed on the basis of an identical idea with the SPI system [6]. This special structure appears to be the world's first example of seismic suspension building structure that works very similar to the SPI system conceptually. Figure 1 shows a schematic view of elevation and plan of one of the two buildings. It consists of two triangular-shaped boundary towers which are connected at the top by a huge steel caisson beam from which the central 29-story steel structure has been suspended. Elasto-plastic steel dampers are inserted between the lateral towers and suspended core junctions at each floor levels. The equivalent period of isolated building is about 5 sec, considering the effect of steel dampers as well. By using this model, designers could save a 30% reduction of bending moments and shears at the base of towers.

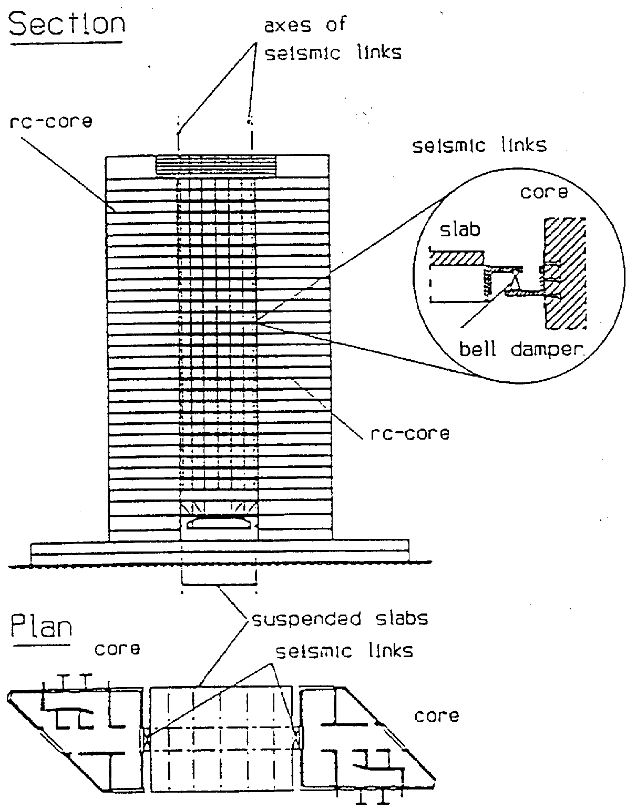


Figure 1. Schematic view of a 30-story suspended tower building constructed in Naples, Italy

(after Chiampi, V. et. al [6]).

In this study the main objective is to evaluate some practical aspects of the SPI system including its applicability, what advantages it offers in comparison to other existing systems, its effectiveness against various types of earthquakes--specially near-field motions with low-frequency contents, and its cost-effectiveness. For this purpose, results of an experimental model consisting of a test structure isolated by SPI system has been examined through energy analysis. A case study for 5, 10 and 20 story moment resistant frame buildings is investigated and compared for isolated and conventional designs. Several number of specific accelerograms recorded in near-fault distinct having peak velocities higher than 100 cm/sec are considered [4,5].

DESCRIPTION OF TEST DESIGNS

Test model consists of a generalized steel structure supported by the SPI as isolator, and a pair of multi-layer lead dampers. Test structure with the fundamental period of 0.162 sec, corresponding to the period of 0.405 sec in prototype size, has been selected as a representative of low-rise building (i.e. five-story frame structure) which is usually main target of base isolation systems. It is worth noting that higher modes of structure in the isolated case primarily have very little participation in responses, therefore the simplified model could provide sufficient accuracy in the research that this report is part of it [3].

The isolation system is a prevalent model of the SPI system originally designed for 2-sec period [1], but its fundamental period is extended later to much longer periods, i.e. up to 6 sec, based on a design of adjustable length of pendulum [2-5]. Isolator periods of 0.8 sec, 1.6 sec and 2.4 sec (i.e. 2 sec, 4 sec and 6 sec in full-scale size, respectively) for the SPI system were tested. The multi-layer U-shaped lead damper was found to be an effective energy absorber for all the considered range of periods. Its versatility in design and practice provided such opportunity to examine several yield strengths for each case of SPI period and to find out the most appropriate properties for each case. For instance., sizes and dimensions of lead segments were designed to have five levels of yield strength as 1.5, 3.0, 4.5, 6.0 and 7.5 per cent of total weight (W) of super-structure for the SPI period of 6 sec.. For further information on other periods and how to assess the optimum yield strength in lead dampers, interested readers may refer to previous studies [2,3]

The time history records of actual ground motions from several well-known earthquake prone regions are used as input signal to the shaking-table. In this study, however, main focus is on those records with specific characteristics which are assumed to be potentially destructive to flexible structures including seismically isolated buildings. These include NS component of Takatori station (from 1995 Hyogoken-Nanbu earthquake), NS component of Sylmar station (from 1994 Northridge earthquake), EW component of Mexico-City (recorded on soft-soil layers of alluvium during 1985 Mexico-City earthquake), EW component of Tabas station (from 1978 Tabas-Iran earthquake), and finally NS component of El Centro station (from 1940 Imperial Valley earthquake) for comparison basis. Table 1 summarizes some of their important properties from design perspective view.

Table 1. Peak values of input earthquakes and their strongest range of period contents

Input Earthquakes	Acceleration (gal)	Velocity(cm/sec)	Displacement(cm)	Predominant rangeof period (sec)
El Centro	341.70	33.86 (13.54)	–11.06 (–1.77)	0.2~1.0 (0.08~0.40)
Mexico City	-167.92	-60.42 (24.17)	20.60 (3.30)	2.0~3.0 (0.8~1.20)
Takatori-NS	605.50	119.40 (47.76)	44.08 (7.06)	1.0~2.5 (0.04~1.00)
Sylmar -NS	826.76	–128.88 (–51.55)	–32.55 (–5.21)	0.5~3.5 (0.10~1.40)
Tabas	907.45	-109.36 (43.74)	44.36 (7.10)	0.5~6.0 (0.04~2.40)
Mean values*	779.90	119.21	40.33	

* Mean values are related to three near-field records, thus excluding El Centro and Mexico-City motions

Peak velocity is mainly viewed as a better indicator of exciting energy, thus it may offer more realistic evaluation of damage potential than peak acceleration. For seismic isolation system ground displacement is also very important, because the damage potential may depend on how much peak bearing displacement occurs during such velocity pulses. Another significant factor in destructive property of a strong ground motion would be its frequency contents. Evidently, as shown in 5th column of Table 1, all of the earthquake motions recorded in near–field and soft-soil areas have considerable energy at long periods ranging from 1 to 3 sec.

ANALYSIS OF TEST RESULTS

In previous studies, the performance of the SPI system for several strong ground motions was evaluated considering absolute acceleration at top of the isolated structure and bearing displacement at base. This methodology is certainly useful to compare the effectiveness of seismic isolation types, since these values are basically needed in design procedure to decide on the level of target safety in different levels of earthquake forces.

To provide much deeper understanding of dynamic behavior, energy analysis for those results is conducted herein. A simulation model which verifies the experimental results is developed using DRAIN-2DX modules [13]. In this precise model, properties of all the elements including framed super-structure, isolation system and lead dampers are defined based on experimentally measured characteristics so that with identical input earthquake excitation, similar output as of recorded signals could be achieved. A non-linear step-by-step time history analysis lead to a satisfactory results for the acceleration, displacement and inter-story drift of very same isolated test structure.

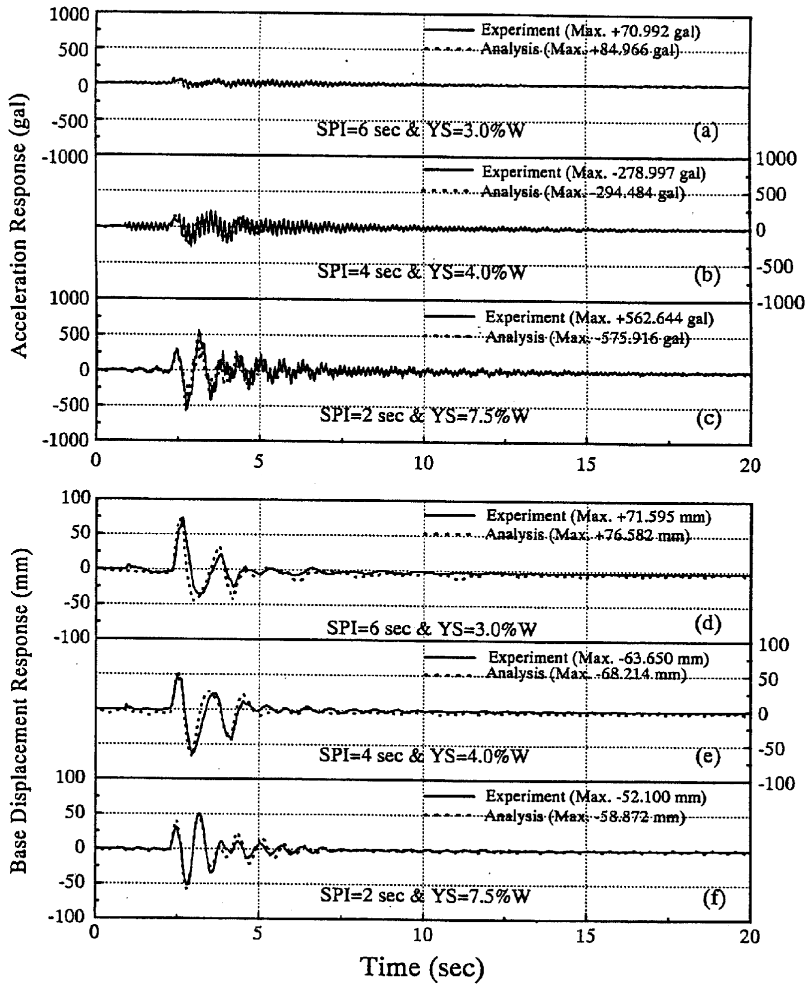


Figure 2. Comparison between analytical and experimental responses for isolated structure using SPI system associated with lead damper under Sylmar-NS excitation

Figure 2 compares the simulated and tested results for an identical frame structure isolated by the SPI system (at the condition of various periods) under NS component of Sylmar excitation. As shown in this figure, the absolute acceleration responses at top of the isolated structure and relative bearing displacement responses at interface level of isolation are in agreement well. Furthermore, the order of accuracy for the inter-story deformation responses are also acceptable. It is important to note that almost similar order of accuracy are achieved under other excitation sources, earlier stated in Table 1.

As noted before, the main aim of this analysis was to calculate various energy time-histories quantitatively including the damping (those of both dissipated hysteretic and viscous portions), the structural (strain energy restored in structural elements) and kinetic energies. Figure 3 displays these energy quantities separately for an identical case of isolated structure under various excitations. In this case, it is considered to have SPI system of 6-sec associated with lead damper of 3%W as yield strength which results in equivalent period of about 4.6 sec in whole isolated system.

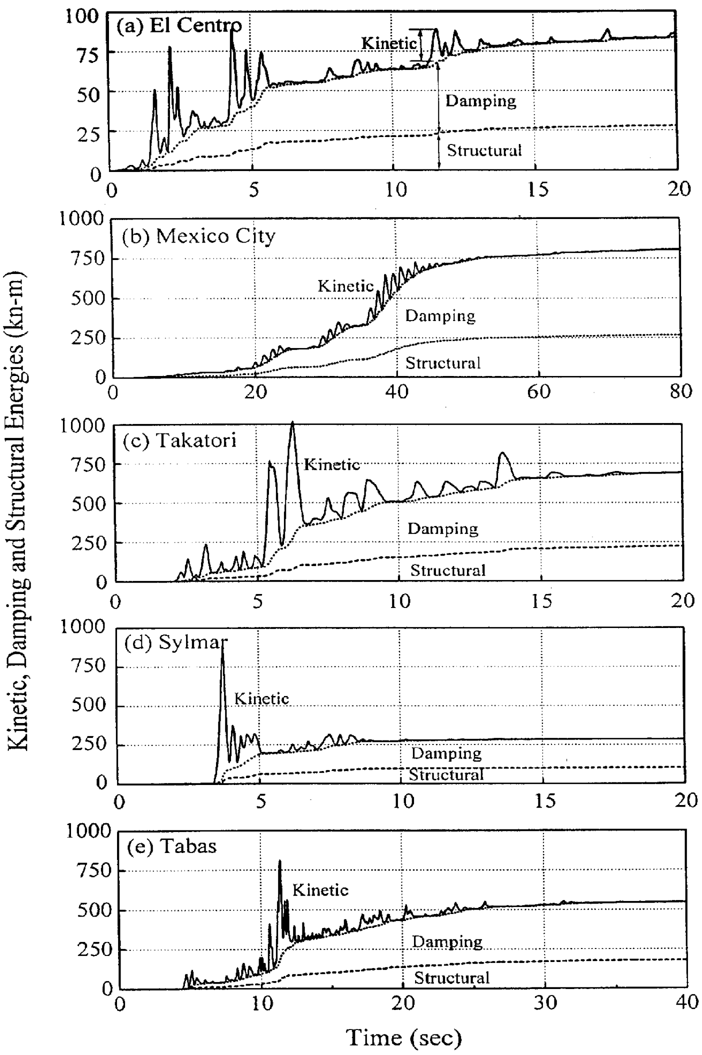


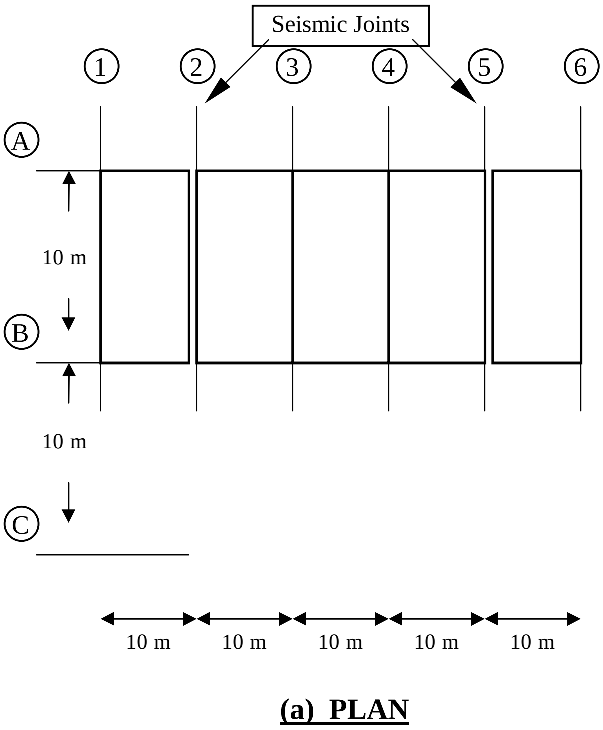
Figure 3. Energy distribution in the seismically isolated structure using SPI system with nominal period of 6 sec, under exciting earthquakes in the shaking-table tests

The first important observation to be made from Figure 3 is that the order of energy quantities for El Centro earthquake stands at almost one-tenth of other excitations' corresponding cases. This fact could not be realized in either peak acceleration or peak velocity comparison, therefore, it is very crucial in evaluation of dynamic behavior of isolated system. It is obvious that even for El Centro excitation adjusted to three times larger peak velocity (e.g. about 110 cm sec), kinetic energy of isolated structure would be much less than those of near-source motions such as Takatori and Tabas.

Another substantial observation from this figure to be pointed out is that in the case of a large pulse shock waves such as Sylmar excitation, flexible isolated system has lower range of dissipated damping energy, although the system appears to be effective in reduction of peak acceleration and drift index. Thus, peak values of kinetic energy has a minor effect in effectiveness. Figure 3(b) is supporting this idea well. The energy analysis for Mexico-City excitation indicates that for small peaks of kinetic energy but several cycles, damping energy becomes very high in comparison with near-source motions. This is while the peak input acceleration of Mexico-City (recorded on alluvium layer) is four times less than that of mean peak acceleration (see Table 1).

SAFETY ASSESSMENT AND COST-EFFECTIVENESS OF SPI SYSTEM IN PRACTICE

To analyze the economic effects of the new system in practical design of structures, a frame building superstructure with regular plan (2 by 5 spans, each span of 10 m) and uniform shape is considered in numerical model. Height of building is assumed to be 20, 40 80 meters (i.e. 5, 10 and 20 stories, each story of 4 m). These dimensions are chosen deliberately so that the results can be compared with those results of similar isolated buildings using LRB system [13]. These target structures are supposed to be suspended at roof from deep girders of the external premier structure using suspension cables, as demonstrated schematically in Figure 4. Note that U-shaped lead dampers of the same form as experimental test are distributed in seismic joints (clearance zone) at required floor levels to be effective in both horizontal directions.



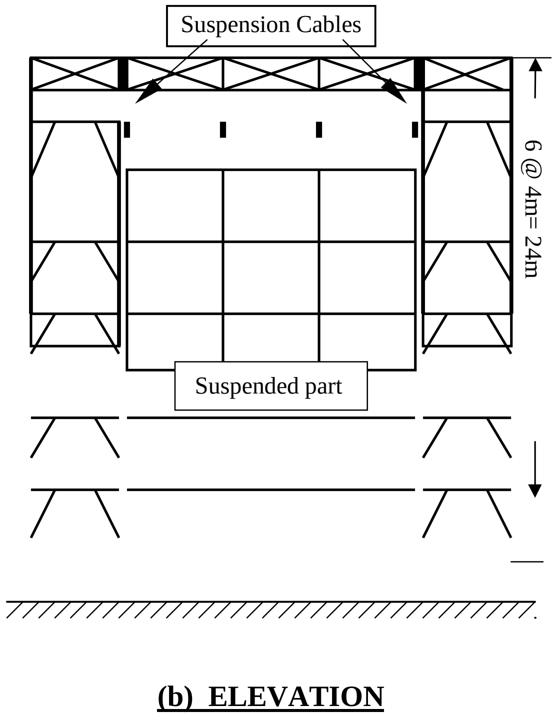


Figure 4. Schematic view of analytical model consisting of frame super-structure and SPI system

Design earthquake is considered to be the dominant ground motion listed in Table 1. Gravity and live load is a uniform 15 kn/m^2 for all stories [7], and are assumed to be put as lumped mass at beam-column joints. Results of non-linear analysis for three isolated buildings are classified in Table 2 and compared with the same but non-isolated structure. Since construction cost varies from region to region, comparisons are made for volume of main element materials (all supposed to be steel for simplification). Equivalent period of isolated building is calculated for whole suspended building considering also lead dampers rigidity in conjunctions.

As displayed in Table 2, maximum acceleration responses at top of the isolated buildings and drift indices are almost ten times smaller than those of corresponding values in the fixed structure. Peak bearing displacements which refer to displacement of target building relative to SPI system are below 45 cm, hence even a 50 cm moat (clearance zone) could prevent any impact between isolated building and its premier structure. These values are comparable with the corresponding results of 200, 220 and 240 gal for 5, 10, 20 stories, respectively, using lead rubber bearing isolation system under excitation adjusted for 150 cm/sec [16].

Comparison of maximum base shear ratios indicates that the base shear of isolated building stands at the safe margin of 0.2W (W is total weight of building) in all three conditions, while the shear forces in fixed building

exceed the margin largely. The similar trend also exist for maximum moment at base. It is important to note that overturning moment should not exceed the limit of 0.5W.D (D is building width, 20 m in Fig. 4), otherwise pile foundation type would be required. Therefore, maximum base moment ratios in Columns (2), (4) and (6) show at least a safety factor of 2.5 for isolated condition.

Table 2: Comparison of numerical results for isolated and fixed structures

	5-story building		10-story building		20-story building	
	Isolated	Fixed	Isolated	Fixed	Isolated	Fixed
Equivalent/Natural period (sec)	4.75	0.42	5.64	0.84	6.33	1.71
Yield Strength ratio (%W)	3.50	----	3.00	----	2.50	----
Effective damping ratio (%)	9.55	3.00	8.60	3.00	7.92	3.00
Max acceleration (gal)	210.24	1850.86	146.75	1370.23	114.50	1106.95
Max bearing displacement (cm)	33.75	----	38.62	----	44.94	----
Max drift index	0.0030	0.0330	0.0024	0.0284	0.0018	0.0215
Max base shear ratio (F/W)	0.184	0.691	0.139	0.569	0.106	0.423
Max base moment ratio (M/W.D)	0.121	0.445	0.178	0.573	0.209	0.784
Material volume ratio (V'/V)	1.02	1.00	0.98	1.00	0.95	1.00

It is observed from this table that isolated condition offers superior safety, while it may also stand cost-effective for taller building than 5-stories. Note that additional structural elements at top floor for the isolated case are part of element volume saved from force reduction effect due to less seismic forces. This make the structural volume of whole system stand 2 and 5 per cent lower than their fixed conditions in 10 and 20 stories, respectively It should be mentioned that this is a simplified case of a small plan, therefore, for larger buildings expanded in both horizontal and vertical directions, the SPI system can be designed to fit the economic limitation for even low-rise buildings. Furthermore, the SPI system is almost unconditionally stable since none of the rollover and shear strain capacities restrict its stability

CONCLUSIONS

The main objective of this paper was to evaluate the applicability of a new suspension isolation system (SPI) form practical point of views; namely any advantages in comparison to other existing systems, its effectiveness against various types of earthquakes through energy analysis, and its cost-effective performance at required safety margin. For this purpose, results of an experimental model which had been tested utilizing shaking-table facility were analyzed. The test model was designed as a way to be adjusted for conducting various period of isolator along variety of yield strength for lead damper. Several number of recorded accelerograms including those of Northridge and Hyogoken-Nanbu (Kobe) ground motion signals with peak velocities as high as 130 cm/sec were examined.

To have better interpretation of dynamic behavior, energy analysis for those experimental results was conducted. A numerical model based on DRAIN-2DX modules was developed. In this simulation technique, properties of all elements including framed super-structure, isolation system and lead dampers were defined based on experimentally verified values so that with identical input earthquake excitation, similar output as of recorded signals could be achieved. On the basis of this analysis, energy time-histories including the damping, the structural and the kinetic energies were separately calculated. These energy quantities are found out to be very supportive of realistic observation inconsistent with actual responses.

The design procedure showed that this new system can be practically implemented as suspension tool at roof levels providing longer periods depending on suspension pendulum and yield strength of lead damper. Results also indicated that transmitted acceleration to the isolated structure could have been attenuated effectively for all type of considered ground motions. This system was able to accommodate large ground displacement of near-source pulse waves in which bearing displacement may reach large peaks. It is also important to note that the stability of SPI system at its ultimate capacity is guaranteed. Results of a case study for 5, 10 and 20 story frame buildings showed that utilization of the SPI system is economically comparable with conventional design, while providing much higher level of safety margin. It is anticipated that results achieved in this research could be put in practice and serve as a design technique since it incorporates a multi-parameter for design variables

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REFERENCES

1. Bakhshi, A., Araki, H., and Shimazu, T. (1998), "Evaluation of the performance of a suspension isolation system subjected to strong ground motion", *Earthquake Engineering. & Structural Dynamics, Vol.27, No.1*, pp.29-47.
2. Bakhshi, A., Araki, H. and Shimazu, T. (1998), "Experimental study on application of super long-period seismic isolation systems for near-source earthquakes", *Proceedings of the 11th European Conference on Earthquake Engineering*, Paris, France, CD ROM, paper No.363.
3. Bakhshi, A. (1998), *Experimental and Analytical Study on a Suspension Seismic Isolation System Subjected to Strong Ground Motions*, Ph.D. Dissertation, Hiroshima University, Japan.
4. Bakhshi, A., Shimazu, T. and Araki, H.(1998), "Experimental and analytical study on a suspension seismic isolation system subjected to strong ground motions", *Proceedings of the 10th Japan Earthquake Engineering Symposium*, Yokohama, Japan, pp.2879-2884
5. Bakhshi, A., Araki, H. and Shimazu, T.(1998), "Shaking-table tests on super long-period seismic isolation systems for near-source earthquakes", *Proceedings of the 2nd World Conference on Structural Control*, Kyoto, Japan, Vol. 2, pp.1161-1170.
6. Ciampi, V., Angelis, M. D., and Paolacci, F. (1998), "Energy dissipation techniques for earthquake protection of civil buildings in Italy", *Personal Comm*unication.
7. International Conference of Building Officials--ICBO (1997), *Uniform Building Code*, Whittier, California, USA.
8. Kelly, J.M. (1995), "Seismic isolation engineering", *Proceedings of 2nd International Conference on Seismology and Earthquake Engineering*, Tehran, I.R. of Iran, pp1075-1094
9. Krishna, P..(1978), *Cable-Suspended Roofs*, McGraw-Hill, New York, pp314
10. Mayes, R.L. Jones L.R. and Kelly, T.E..(1990), "The economics of seismic isolation in Building", *Earthquake Spectra, Vol. 6, No. 2*, pp.245-263.
11. Mokha, A.S. and Fatehi, H (1997), "Designing base-isolated structures for near-field effects", *Building to Last, Proceedings of Structures Congress XV sponsored by ASCE*, Portland, Oregon, April 1997, pp1565-1568
12. Naeim, F. and Kelly, J.M. (1999), *Design of Seismic Isolated Structures; from Theory to Practice*, John Wiley &Sons, New York, pp289.
13. Prakash, V., Powell, G.H., Campbell, S. (1993), *DRAIN-2DX Base Program Description and User Guide*, Ver. 1.10, November 1993, The University of California at Berkeley
14. Pugsley, A.Sir.(1968), *The Theory of Suspension Bridges*, Edward Arnold, London, pp155
15. Shimazu, T. (1998), "Evaluation of base isolation systems based on recorded and predicted responses of actual buildings under recent earthquakes", *Proceedings of the 2nd World Conference on Structural Control*, Kyoto, Japan, Vol. 2, pp.1145-1152.
16. Skinner, R.I., Robinson, W.H. and McVerry, G.H.(1993), *Introduction to Seismic Isolation*, John Wiley &Sons, England, pp355.
17. Stanton, J. and Roeder, C.(1991), "Advantages and limitations of seismic isolation", *Earthquake Spectra, Vol. 7, No. 2*, pp.301-324.
18. Takayama, M. and Morita, K. (1996), "A study on the energy approach of base-isolated structures", *Proceedings of the 12th World Conference on Earthquake Engineering*, Acapulco, Mecico, CD ROM, paper No.1504.

Zayas, V.A., Low, S.S. and Mahin, S.A. (1990) "A simple pendulum technique for achieving seismic isolation", *Earthquake Spectra, Vol. 6, No. 2*, pp317-333.