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WORLDWIDE DEVELOPMENT OF FRICTION SEISMIC ISOLATION SCHEME FOR MASONRY BUILDINGS

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ABSTRACT

Although the concept of seismic base isolation as a means of earthquake protection seems to be more than a century old , most of the proposed systems are unacceptably complicated . But , in recent years a few practical systems have emerged in which the superstructure is connected to the foundation through flexible elements and / or energy dissipation devices are introduced. Masonry buildings of conventional construction cannot be economically isolated by these techniques. In view of these problems, the concept of friction seismic isolation (FSI) for masonry buildings has been developed .The paper presents a review of worldwide development of such a FSI scheme in which isolation mechanism is purely sliding friction for masonry buildings. Initially, a feasibility study of the FSI concept was undertaken by testing pilot brick house models using different sliding materials which were interposed between the superstructure and substructure. It was observed by testing of the models on the shaking table that in the case of friction base- isolated models, there is no amplification of accelerations which occurs normally in the fixed-base models. Further, more house models were constructed employing different scales and materials and tested on the shaking table. The comparisons show a good general agreement between the experimental and theoretical results. In view of such studies, four demonstration brick buildings have been built in China using FSI scheme. Thus, the FSI system is an attractive one for low-cost housing since it can be constructed by using no more complicated technology or no more skilled labor than a conventional structure.

KEYWORDS

Friction seismic isolation; isolation mechanism; Dhubri earthquake; sliding joint, coefficient of friction; feasibility study; graphite powder; asphalt felt; nondimensional acceleration; stiffness ratio.

INTRODUCTION

The conventional masonry buildings have very poor safety records during past earthquakes. The masonry construction will continue to be the most common mode of building construction in all countries except perhaps in the relatively more developed ones. In order to improve the seismic behavior of masonry buildings, strengthening measures as recommended by design codes (A world list, 1992) and guidelines (Guidelines, 1986) for achieving non-collapse masonry constructions did not perform satisfactorily during severe ground motions. Such observations were made after earthquakes in recent past in China, India, Iran, Japan, Turkey, USA and former USSR.

A number of base isolation techniques have been developed and implemented (Buckle et al., 1990, Kelly, 1986) in which the superstructure is connected to its substructure through flexible structural elements and /or energy dissipation devices. However, masonry building cannot be economically isolated by these techniques in developing countries. Friction seismic isolation (FSI) scheme developed during the last twenty years may be employed in masonry buildings economically and with no special technique required in their construction. The paper presents briefly a review on the worldwide development of FSI scheme.

CONCEPT OF FRICTION SEISMIC ISOLATION

Seismic base isolation consists of decoupling the structure from the damaging effect of horizontal component of the earthquake ground motion. The main idea for solving the seismic strength problem of masonry buildings has come from the past history of earthquakes. After the Dhabi earthquake, the damage study (Gee, 1934) showed that those buildings in which the possibility of movement existed between the superstructure and substructure suffered less damage than those buildings in which no such freedom existed. Based on such encouraging seismic behavior of small structures, a simple mathematical model was first introduced by Qamaruddin (1978) to compute the seismic response of masonry building with friction base isolation system. In such buildings, a clear smoothened surface is created at plinth level on which the superstructure simply rests and is free to slide except for frictional resistance . This discontinuity at the plinth level enables the building to dissipate a part of the seismic energy by sliding. The FSI concept was established through analytical and experimental studies (Qamaruddin, 1978) made mainly for masonry buildings.

The concept of FSI system was further strengthened by the damage studies made (Li, 1984) after the Xintai (1966), Bohai (1969) and Tangshan (1976) earthquakes in which it was found that adobe buildings which were free to slide on their foundations (by accident) survived with little or no damage whereas others which were tied on their foundations collapsed. Experimental and theoretical studies have been made by researchers to incorporate such a friction seismic isolation system in masonry buildings to achieve damage free performance during the earthquakes. In the following paragraphs, both types of studies are briefly described.

EXPERIMENTAL STUDIES

Experimental investigations, which were carried out to study the dynamic and seismic response of the masonry structural models, are briefly discussed in the following sections to show the effectiveness of the FSI concept .

Tests on One-Fourth Scale Single Story House Models

Feasibility study of the concept was worked out by testing (Qamaruddin, 1978, Qamaruddin et al., 1984) pilot house models, by inserting different sliding materials (such as graphite powder, dry sand and wet sand) between the house models and their base. The observed coefficients of friction (F) were 0.25 for graphite powder, 0.34 for dry sand and 0.41 for wet sand. By steady-state testing of the pilot models, it was observed that, in the case of base isolated models there is no amplification of acceleration, the type of which occurs in the case of fixed-base low-period structures. Using graphite powder as a sliding material, the ratio of top/base acceleration was nearly equal to 0.63, which, for the same model fixed at the base, was as high as 2.34. Thus, the preliminary tests on base isolated models strengthened the concept that by introducing a discontinuity at the plinth level of the superstructure, the effective seismic force can be reduced as compared to that of the conventional models.

Dynamic Load Tests on Single Story House Models

The experimental investigations were carried out by the researchers to study the dynamic behavior and to compare the performance of the FSI house models with that of the conventional ones. These models were fabricated with different aseismic schemes and subjected to (a) shock load , and (b) blast induced strong ground motion.

Small Scale Models. Eight half-scale models of typical brick house were tested (Qamaruddin, 1978, Qamaruddin et al., 1984).Out of eight models, there were six conventional ones, and two with a sliding substructure (Fig. 1). Besides the features of fixity or sliding at plinth of model, the quality of mortar, wall thickness and reinforcing patterns were also varied. The test on these models were carried out in two sets of four each on a specially fabricated railway wagon shock table facility. It turned out from the tests that the house specimens with sliding permitted at the base had a significant reduction in response and adequate behavior up to very high base accelerations as compared to the similar models with fixed base.

Five small scale house models were tested (Li, 1984) on shake table to examine the effectiveness of FSI system. All the five house models survived the shaking of the table and the sliding of the superstructure was observed at 0.2g acceleration of the table .

Model studies were carried on aluminum and masonry specimens with FSI scheme (Zongjin et al., 1989). Four series of tests were run with the base of the structure fixed, followed by one series of tests for each of the three sliding materials. Fig. 2 shows the comparison of acceleration spectrum of experimental response with the theoretical response for both the fixed and the sliding structure. There is reasonably good agreement between the experimental and theoretical results for the sliding structure.

Horizontal load and distortion tests of brick walls with and without sliding joint under various vertical loads were made by Lou et al. (1992). Results showed that the horizontal load of the conventional wall, when the formation of cracks started, was two times larger than that of the wall with sliding joint. Shaking table tests were also made (Lou et al., 1992) with various sliding joint specimens. Graphite powder, asphalt felt, screened gravel or fine sand and paraffin wax were employed as sliding material . The test results showed that the graphite was an ideal low friction material to make sliding joint.

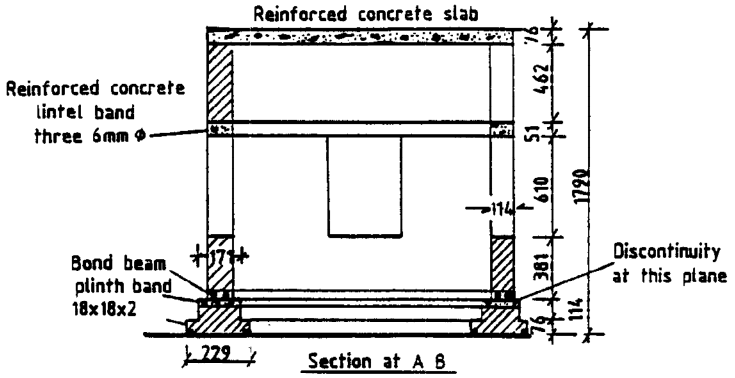

Fig. 1. Brick house model for sliding base

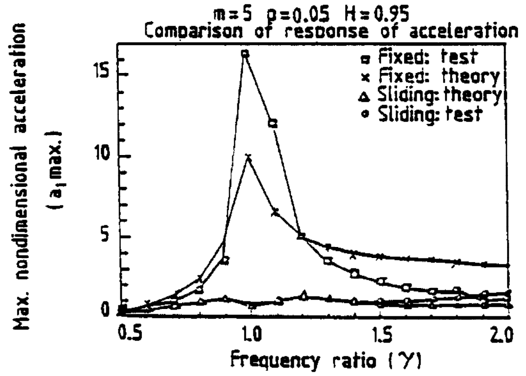

Fig. 2. Comparison of acceleration spectrum values (analytical and experimental)

Testing of Full-Scale Model. One full-scale FSI house model, constructed with underfired bricks of low strength, was tested by blast-induced loading, equivalent to high intensity earthquake (Li, 1984). The model survived the blast loading and shifted a little distance at the base.

Shaking Table Test on Multistory House Models

Bingze et al. (1990) tested two six-story reduced scale gypsum models on shaking table to investigate dynamic behavior and sliding-rocking mechanism of isolated base multistory brick buildings. One of the models had FSI scheme (model 1) whereas the other model was fixed directly on the shaking table (model 2).

The FSI stratum was composed of upper and lower reinforced concrete ring beams filled with two layers of asphalt felt in which graphite powder was interposed. The models were excited on the shaking table with input acceleration varying from 0.1g to 5g. Sliding was initiated at 0.25g acceleration in model 1. No damage was seen in model 1 up to 5g base acceleration. The model 2 collapsed at the end of the test.

Construction of Experimental Buildings with FSI Scheme

Four buildings with the FSI measure were built in China (Li, 1984). One 16 m^2 adobe house with straw roof was constructed at Huaping County (Yunnan Province) in 1975. Another 16 m^2 house with tamped wall and tile roof was built at Xichang city (Sichuan Province) in 1975. In 1980, a 12 m^2 house was built with brick wall and tile roof at Anyang City of Henan Province. A four-story dormitory was constructed for Strong Earthquake Observation Center at Beijing in 1981.

THEORETICAL STUDIES

The analytical studies made by the researchers, to establish the effectiveness of the FSI scheme for masonry structures, are discussed in the following sections.

Mathematical Model

A single-story masonry house (Fig. 3) was considered (Qamaruddin, 1978) to introduce for the time the concept of FSI by providing sliding base in the structure. A thin layer of sliding material is interposed between the contact surfaces of bond beam of the superstructure and plinth band of the substructure. The structure is idealized as a discrete model with two-degree-of-freedom as shown in Fig. 4 for its seismic response computation. The bottom mass of the FSI system either stops or continues to slide throughout the time history of earthquake ground motion. Numerical integration of the equations of motion has been made employing Runge-Kutta fourth order method.

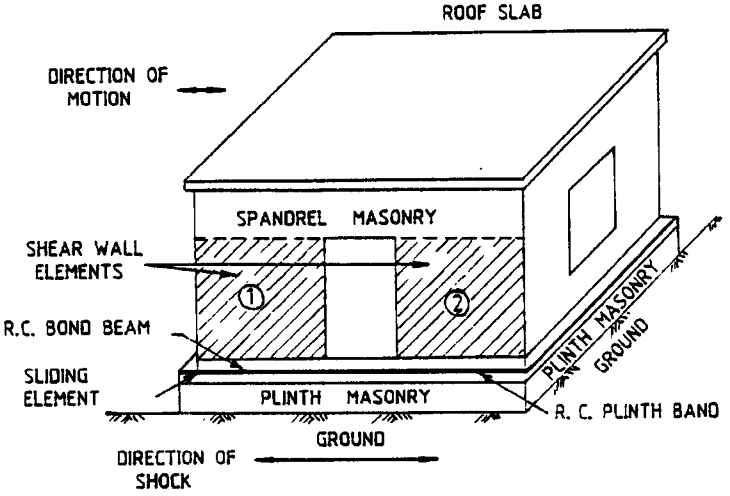

Fig. 3. Idealized friction seismic isolated brick house

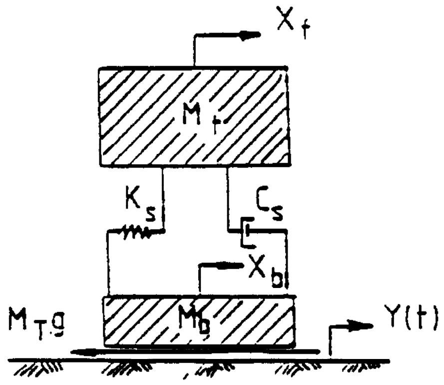

Fig. 4. Mathematical model

Responses to Earthquake Excitations

A range of parameter values representing the physical properties of masonry building was employed to arrive at generalized results (Qamaruddin, 1978, Qamaruddin et al., 1986, 1986a). The parameters are: time period, mass ratio, dry frictional damping and viscous damping . The response was determined using El Centro earthquake of 1940, California , USA and Koyna earthquake of 1967, India. The results of the seismic response computation are presented in the form of frictional response spectra. Representative results of the spectra developed (Qamaruddin, et al. , 1986a) are shown in Fig. 5. It is seen from these figures that the spectral acceleration decreases as the coefficient of friction (F) decreases. Unlike the fixed-base structure, the frictional spectra are generally flat and the values does not change much as the period of the system as well as other parameters are varied. These figures also show that generally acceleration of the FSI system is much less than that of corresponding fixed-base system subjected to earthquake ground motion. From this study, it also turns out that the residual displacement is slightly smaller than the maximum dynamic displacement which may be used in the design of structure.

A few years later, Mostaghel et al. (1983, 1983a) presented a similar mathematical model as first proposed by Qamaruddin (1978) for solving problem of single-degree-of-freedom structures supported on sliding substructure and subjected to harmonic and also earthquake support motions. The structures were subjected to 1940 El Centro and 1949 Olympia earthquake (Mostaghel et al. ,1983a). It is observed from the results of this investigation that for structures with time period less than 1.8 seconds the maximum, sliding and residual sliding displacements are of the order of 1.25 times the peak ground displacements. It is also noted that increase in the levels of the input excitations increases the FSI system effectiveness in cutting down the acceleration. However, no attempt was mode to compare the analytical results with that of the experimental studies.

A comparative study of effectiveness of various base isolators was carried out (Su et al., 1989). Results of responses of a rigid structure with various base isolators to accelerograms of El Centro 1940 earthquake and Mexico City 1985 earthquake are evaluated. Based on the presented results, it may be concluded that, for relatively rigid structures, the FSI system is less sensitive to the undesirable variations in the frequency contents of ground excitation. Furthermore, due to their high energy dissipation capacity, the FSI system can effectively reduce the transmitted acceleration with limited sliding displacements.

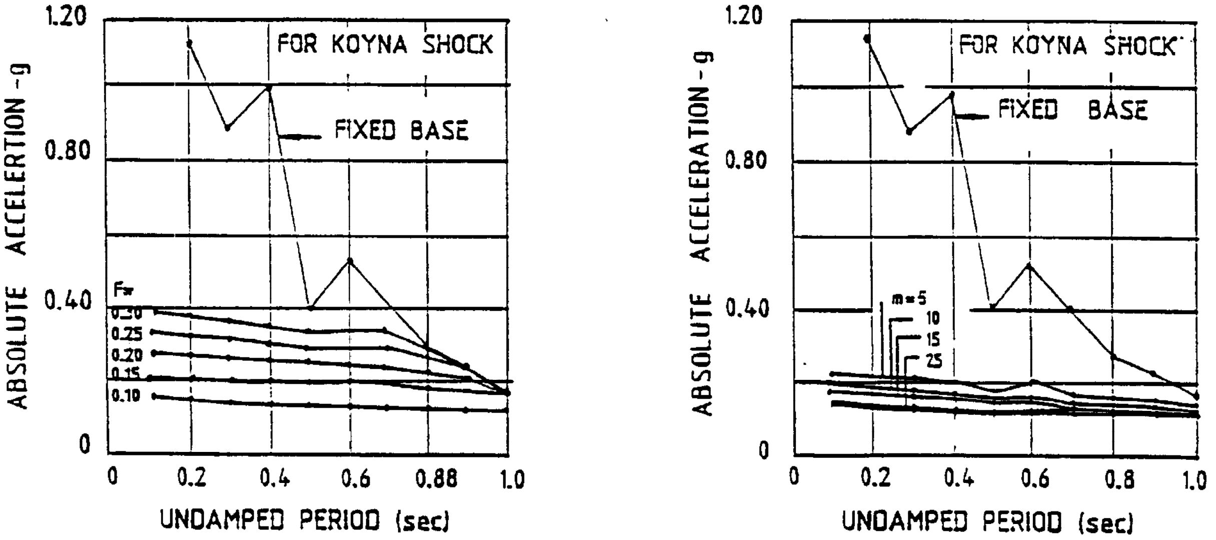

Fig. 5. Acceleration frictional response spectra

Responses to Dynamic Excitations

The normalized acceleration spectrum for sliding structures subjected to harmonic support motion is shown in a representative Fig. 6 (Mostaghel et al., 1983). It is seen from Fig. 6 that the spectral response of the isolated structures appear to be independent of frequency whereas the level of the response depends only on the coefficient of friction on the base. The response level of the sliding structures is considerably less than that of the corresponding fixed-base structures. The sliding displacement is larger for smaller coefficients of friction while it does not vary significantly with frequency ratio.

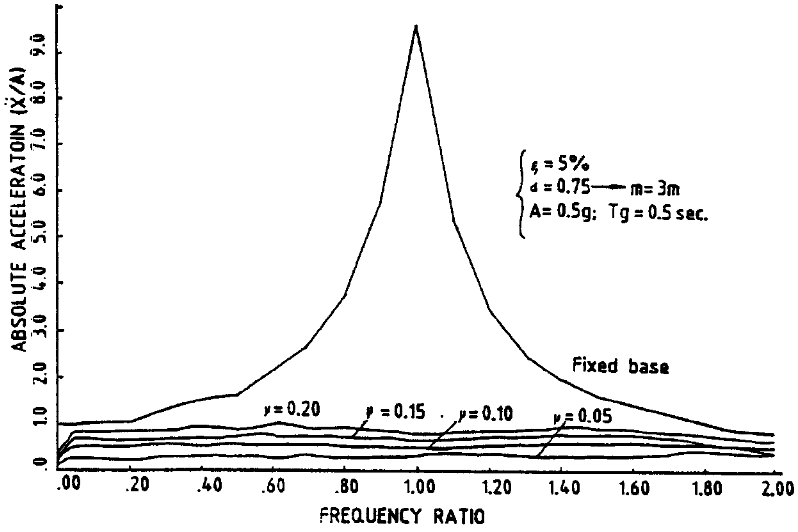

Fig. 6. Variation of acceleration with frequency ratio

The response of the sliding system subjected to the forced vibration was determined by Zongjin et al., (1989) employing the same mathematical model as introduced earlier by Qamaruddin (1978) and used by other researchers (Arya 1984, Qamaruddin et al., 1986, 1986a). The analytical results showed that the absolute acceleration of the superstructure was significantly reduced from the fixed-base condition. The results also demonstrated that the response of the sliding structure was nearly independent of intensity of the input motion.

Response of Multistory Buildings with FSI Scheme

The response of multistory buildings with interfloor discontinuity at different story - levels and at the base was studied (Qamaruddin et al., 1986b) by representing the system with two rigid blocks, each block replacing several stories clubbing together. A layer of suitable sliding material was interposed between the contact surface of bond beams of the first and second blocks of the superstructure and between the bond beam of the superstructure and plinth band of the sliding substructure. The seismic response was computed for 1940 El Centro earthquake and Koyna shock of 1967. It turned out form the results that the spectral acceleration of the sliding system is less than that of the corresponding fixed- base system.

A mathematical model for multistory masonry building with FSI scheme was introduced by Qamaruddin et al. (1990) . The structure is idealized as three-mass-spring-dashpot model with one degree of freedom per mass. The system was subjected to 1940 El Centro shock and 1967 Koyna earthquake. A wide range of parameter values were chosen so that the results of the seismic response could be generalized . The spectral acceleration was determined for various values of stiffness ratio, mass ratio, coefficient of friction and system damping ratio. The results show that the absolute spectral acceleration of the system does not vary much for different parameter combinations. From the analysis, it is also observed that the response level of the sliding structures is lower than that of similar fixed-base structures.

Bingze et al. (1990) introduced a mathematical model for dynamic analysis of multistory masonry building with sliding-rocking system considering it as a multiple-degree-of-freedom in shearing mode. The sliding system was subjected to earthquakes of 1940 El Centro, Luan-he 1976 (China), Tianjin 1976 (China). It is concluded from this study that the efficiency of FSI system increased as the peak ground acceleration increases and /or the coefficient of friction decreases. Dynamic response of the isolated system , considering the coupled horizontal and vertical ground motion, was also studied (Bingze et al., 1990). The results of the investigation show that the vertical component of the earthquake ground motion is not much sensitive to sliding motion of the structures.

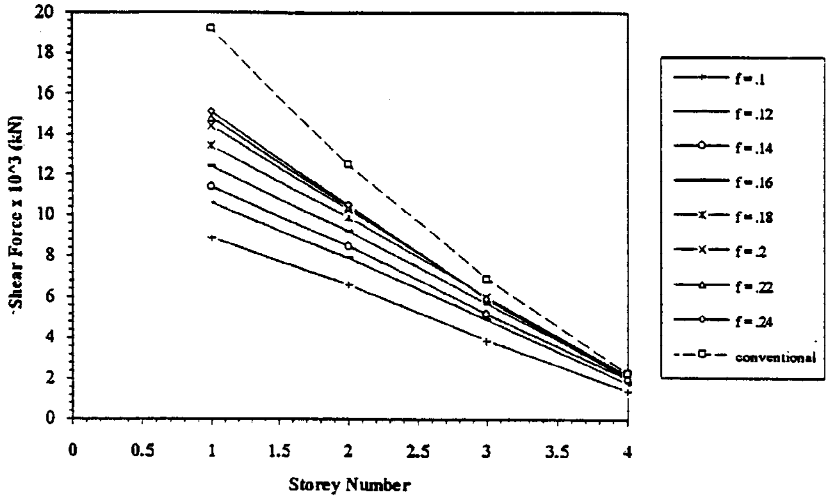

Fig. 7. Shear force variation in masonry building subjected to Koyna earthquake

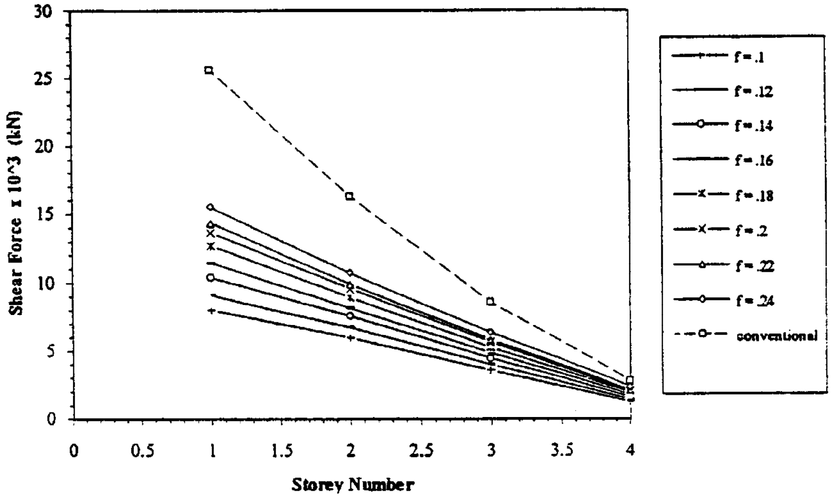

Fig. 8. Shear force variation in masonry building subjected to El Centro earthquake

Lou et al. (1990) determined the seismic response of multistory brick buildings with FSI scheme employing a multiple-degree-of-freedom shearing model ignoring the effect of floor rotational inertia. The results of the analysis showed that the seismic response (acceleration and shearing) was significantly limited by using graphite powder or screened gravel as sliding materials at the base of the multistory brick building.

The response of multistory masonry buildings, with FSI scheme, subjected to Koyna and El Centro earthquakes ground motions is computed through a multi-mass-spring-dashpot mathematical model (Qamaruddin et al., 1994). The parameters involved in the seismic analysis are coefficient of friction, number of stories of the building and type of earthquakes. The results are presented through graphs and tables for different parameter combinations. The results (representative Figs. 7 and 8) show the reduction in the response of the multistory buildings with FSI as compared with the corresponding conventional buildings.

CONCLUSIONS

The beneficial seismic performance of the masonry buildings with FSI scheme has been shown by the experimental and theoretical studies as presented in the paper. The system successfully limits part of the seismic input energy transmitted to the structure. Such a system performs almost independently of the dominant frequency content of earthquake excitation. In view of this very important conclusion, the FSI scheme is suitable for the structures located in near- or far-field seismic environment and founded on different soil conditions. The sliding displacements for the FSI system are large but are within manageable limits. From the present study, it may be suggested that the suitable frictional coefficient range for masonry structures would be between 0.10 to 0.20.

The FSI scheme is easy, economically feasible and requires no special technique for the construction of masonry structure. Therefore, it may be concluded that the FSI system is a viable alternative to conventional seismic resistant design, although it is not yet widely accepted in actual building construction, because it is not known as yet on the performance of such system during real earthquakes.

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