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Development of low-cost Seismic Isolation Platform (SIP) for mass implementation in developing countries

Farbod Pakpour[1], Hossein Agha Beigi[2], Constantin Christopoulos[3]

[1] Ph.D. Student, Department of Civil and Mineral Engineering, University of Toronto - Toronto, ON, Canada.
[2] Post-doctoral Fellow, Department of Civil and Mineral Engineering, University of Toronto - Toronto, ON, Canada.
[3] Professor, Department of Civil and Mineral Engineering, University of Toronto - Toronto, ON, Canada.

ABSTRACT

Rapid urbanization of densely populated urban settings in developing countries like India has exposed such areas to greater human and economic catastrophes caused by natural disasters, specifically earthquake and flooding. This highlights the global need for development of affordable, yet robust and resilient housing against such natural disasters. Using base isolation systems is a practical solution to improve seismic performance of structures to the extent that the functionality of the structure is not impaired after the earthquake; however, currently commercially available isolators may be expensive and challenging to implement in residential affordable housings in developing countries. In this paper, a cost-effective seismic isolation platform (SIP) using simple flat sliding isolation bearings is proposed for mass implementation for most commonly designed buildings in urban settings in India without requiring any significant change to current construction practices. To investigate the efficacy of such a basic seismic isolation system, an extensive finite element nonlinear analysis of two RC buildings located in Mumbai was performed: (i) assuming a fixed-base building, (ii) the same building, but isolated using flat sliding isolation bearings. The analytical results demonstrated that base-isolation significantly reduces global responses such as maximum and residual inter-storey deformations of the isolated structure compared to the fixed-base structure. Thus, the seismic performance of the building, even with nominal ductile detailing, was greatly improved, not only ensuring that the building did not collapse, but also reducing the structural damage to a point where the structure could resume its function almost immediately after a major seismic or flooding event. The study also investigates the expected residual deformations of such a system and their impact on the post-earthquake use of these buildings.

INTRODUCTION

Growing urbanization rates have increasingly exposed larger portions of the global population to the high risks associated with natural disasters. It is predicted that by 2050, 70% of the global population will live in cities [1]. Such rapid urbanisation has led to many challenges such as increasing pressure to build cities in hazard prone areas with unclear mandates for disaster risk reduction and with decaying infrastructure, unsafe building stocks, and uncoordinated emergency services [1].

Recent data shows that developing countries are significantly more vulnerable to such risks than developed countries. Between 1980 and 2011, there was a total absolute economic loss of USD 3.53 trillion globally due to natural disasters, mainly earthquakes, floods and storms, of which two thirds were incurred in high-income countries [2]. Although low-income and lower-middle-income countries combined incurred just over 10% of the total absolute losses, they accounted for more than 75% of total fatalities [2]. Moreover, relative to GDP, developing countries incurred the highest economic losses on average as a consequence of natural disasters [2]. Among developing countries, India is one of the top five countries that was frequently hit by natural disasters over the past decade, among which earthquakes and flooding have been the deadliest [3].

Regarding the seismic design of structures, even in developed countries, the most advanced design and construction codes like the National Building Code of Canada (NBCC) [4] and American Society of Civil Engineers (ASCE) [5], only ensure that newly constructed buildings do not collapse during major earthquakes. Yet, a high level of damage and economic loss are expected to occur in these buildings. Once aggregated over thousands of structures in heavily populated urban areas like Mumbai and Delhi, this may result in such a shock to the socio-economic fabric of the city that it can take decades for such regions to recover. On the other hand, currently, there are many seismic resilient systems like base isolation systems available commercially; but these systems are usually expensive in the economic environment of developing countries, require a sophisticated level of engineering and construction practices, and their use in residential affordable housing in developing countries, which are designed for lowest possible cost, are difficult to justify. Practicing engineers in these regions are mostly unfamiliar with the design and analysis of such systems, which makes their implementation even more difficult. Thus, there is a need to develop a new cost-effective resilient system intended for mass implementation in affordable housing in developing countries that not only enhances the performance of the buildings against earthquakes and flooding, but also does not require any significant change to the current construction practice in the region. To this end, the first part of this paper introduces one such proposed engineered resilient system, the seismic isolation platform (SIP), along with a summary of potential simple flat sliding isolation systems that could be used in the proposed SIP. The second part of the paper provides numerical results of two RC buildings located in Mumbai, India: (i) fixed-base building, (ii) the same building, but base-isolated using flat sliding base isolated bearings.

SEISMIC ISOLATION PLATFORM (SIP)

The seismic isolation platform (SIP), shown in Figure 1a, consists of three major portions: the supporting slab, low-cost seismic isolation system, and ground floor columns. Gravity loads and induced lateral loads on the superstructure caused by the earthquake are transferred to the foundation through the proposed SIP. In case of an earthquake, most of the movement of the building is accumulated in this layer while the superstructure that is constructed above remains undamaged. A similar concept to the SIP was previously applied in 2009 after the earthquake in L'Aquila in Italy, referred to as the C.A.S.E project. The C.A.S.E housing project provided accommodation for more than 15,000 people whose houses were unfit to live in after the earthquake. The construction took about five months during which a total of 185 seismically isolated buildings were developed [6]. The proposed SIP differs from the C.A.S.E project in the following aspects:

1. The C.A.S.E project focused on buildings that were three-storey light structures, while in the SIP, multiple structures with different characteristics are intended to be installed on top of the supporting slab. The target superstructures are between five and twenty-storey RC frames since they represent the most common building types in India.
2. Friction Pendulum Systems (FPS) with commercially patented sliding materials were used in C.A.S.E project; but in the SIP, the objective is to design low-cost flat sliding isolation systems consisting of simply adding a readily available sliding material at the base of the structure, that could replace high-end commercially available isolation bearings.

Sliding bearings

A low-cost flat sliding isolation system is the main base isolation system considered for the SIP, in which the seismic force transmitted to the superstructure is limited by the friction force at the sliding interface (Figure 1b). The major design criteria in these bearings is to control the friction characteristics of the sliding system. Friction characteristics of sliding systems mainly depend on the normal stress, sliding velocity, ambient and surface temperatures, surface roughness, and cleanliness of sliding surfaces [7-9].

Flat sliding bearings are not only effective to limit the earthquake force that is transferred to the superstructure, but they are also inexpensive and compact in size. The major advantages of the sliding isolation bearings compared to elastomeric bearings are:

a) Sliding bearings have better stability under extreme seismic events compared to elastomeric bearings [8].
b) The base shear force in sliding bearings is proportional to the mass of the structure. Therefore, torsional behaviour of the superstructure is minimized since the center of mass and the center of rigidity of the sliding support coincide [10].
c) The response of structures with sliding bearings is generally independent of the frequency content of ground motions and therefore they are effective over a wider range of ground motions [11].

The major drawback of flat sliding bearings is their incapability to return the structure to their original position, which might result into large residual displacements after severe seismic events. To control the sliding displacement, friction pendulum systems with restoring capabilities have been developed for practical implementations [8]. As for the proposed SIP, adequate clearance around the SIP system is considered to allow for such residual displacements.

PTFE-steel is one of the sliding systems considered for the SIP. They are the most common materials that have been used in sliding isolation bearings for decades [8]. However, alternative low-cost polymers could also be utilized to further reduce the cost of this sliding interface. Recently, significant research has been conducted to fully characterize the friction characteristics of alternative low-cost polymers that have the potential to replace PTFE [12-14]. Therefore, the robust performance of this sliding interface along with the extensive amount of research on finding low-cost alternative sliding materials have made this approach the most viable option to be used in the SIP. Currently, extensive full-load and real-time velocity component level experiments on selected of low-cost sliding systems are being conducted at the University of Toronto.

Because of the isolating effect of the aforementioned isolation systems, the building units that are located above the SIP layer can be constructed following current Indian design and construction practices, using local contractors without any significant change to current practice. The SIP at the foundation layer for the building also provides opportunities to improve construction speed of the superstructure through adoption of precast construction techniques at a large scale and provides protection against flooding as well.

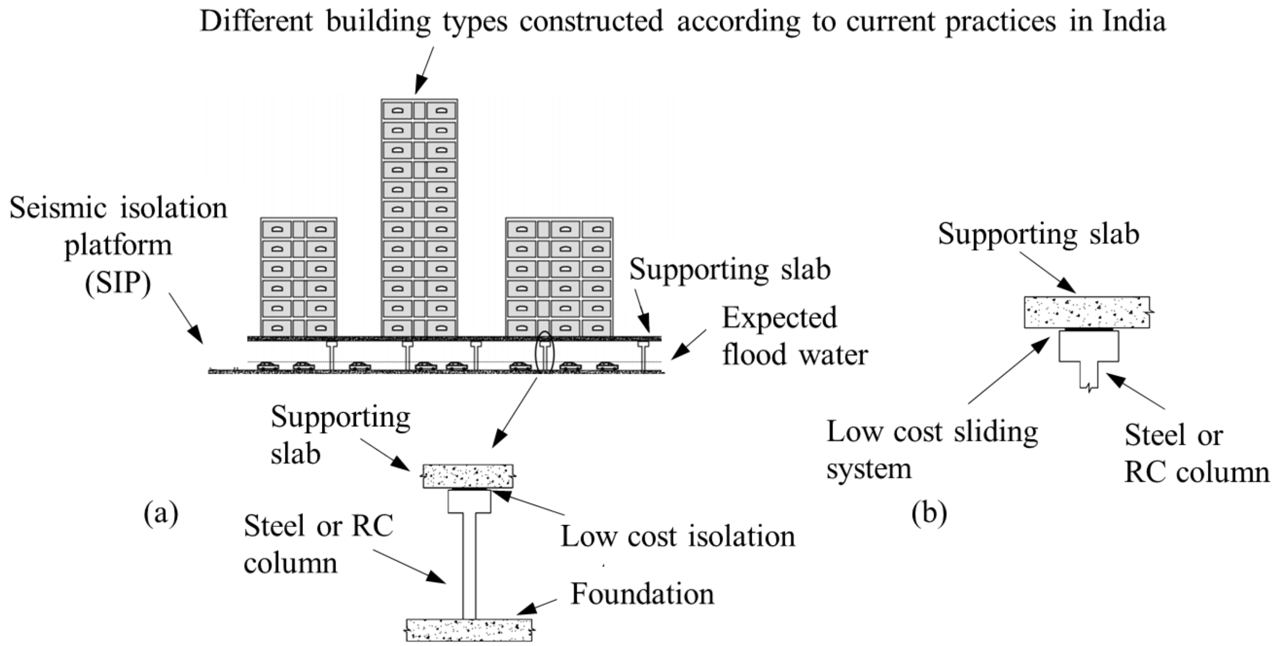

Figure 1. Resilient Seismic isolation platform (SIP) concept built to support buildings: (a) overview, (b) alternative low-cost isolation systems

PILOT STUDY BUILDING MODEL

As a first step to investigate the effectiveness of the SIP for the targeted building archetypes, the most common residential building types for affordable housing in India's large cities like Mumbai and Delhi over the past few decades are identified. According to the results, reinforced concrete (RC) frame buildings ranging from five to twenty stories are considered the most common types of buildings. Consequently, the following building, adapted from a real building design in Mumbai, was selected as the pilot study structure. The objective of this study was to establish a preliminary framework for modeling of this pilot study building in OpenSees [15], and thereby better understand the seismic performance of base-isolated structures with friction coefficients that could be achieved with simple flat sliding bearings versus fixed-base structures that are designed and built in medium to high seismic regions in India.

The building is a nineteen-storey RC residential building located in Mumbai, India (Figure 2). The building is 52 m x 13 m in plan, with a storey height of 3.0 m, except for the first storey, which is 4.5 m high. The fundamental period of the fixed-base structure is 1.9 sec. The seismic force resisting system of the structure is a combination of ordinary shear wall and ordinary moment resisting frames. The building was designed for a seismic zone III (medium seismicity) using the Equivalent Lateral Force (ELF) procedure to meet the requirements of the 2002 Indian Standards: Criteria for earthquake resistant design of structures, IS 1893 (Part 1): 2002 [16].

A three-dimensional finite element model of the building was developed in OpenSees. Finite length hinge forced-based Euler-Bernoulli fiber beam-column elements (BeamWithHinges) was used to model beams and columns. For the concrete and the reinforcing steel, the constitutive models of Park and Priestly [17] and Menegetto and Pinto [18] were used respectively. Shear walls were modeled using the equivalent frame method in combination with rigid links [19]. Rigid diaphragms were used to account for the in-plane stiffness of the slabs. The out-of-plane stiffness of the slabs was excluded. The isolation bearings were modeled using flat sliding bearing elements available in OpenSees. A Rigid Perfectly Plastic hysteretic model was used to represent the horizontal force-deformation relationship of the sliding isolators. A set of three coefficients of friction including 0.03, 0.05, and 0.08, representing typical range of sliding isolation bearings, was considered for the sliding isolators to better define the level of seismic protection needed at the SIP layer to ensure a resilient response during major earthquakes.

To quantify the seismic vulnerability of the building, the performance of the fixed-base and base-isolated structure under nonlinear pushover analysis, nonlinear response history analysis, and nonlinear response history analysis at higher hazard levels was investigated.

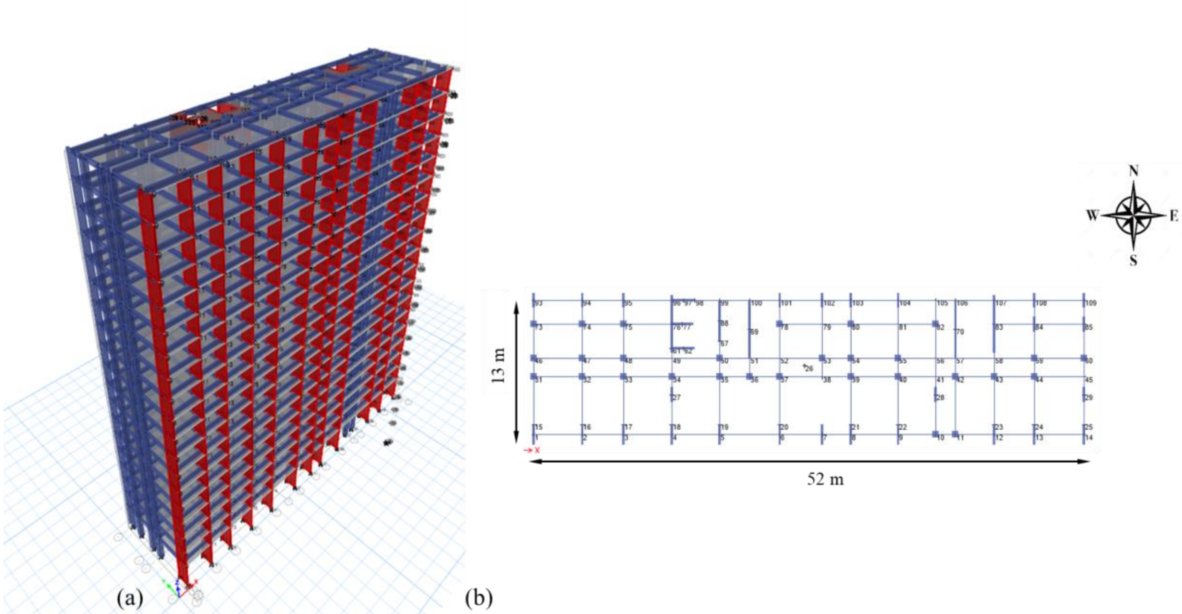

Figure 2. The case study Building: (a) three-dimensional view, (b) plan view

Pushover analysis results

A pushover analysis was performed to investigate the general post-yield load-deformation behaviour of the fixed-base building. the lateral load pattern used was the same as the first-mode shape along the East-West direction as suggested by procedures in the seismic design provisions of FEMA P-695 [20]. The building was pushed up to 800 mm of roof displacement. This method is however of limited accuracy for structures in which higher-mode effects are significant and the load-deformation behaviour is sensitive to the applied load patterns [21].

Figure 3 shows the results of the pushover analysis. The results illustrated a few important model predictions:

a) The peak base shear capacity was about 18000 kN (equivalent to 13.8% of the building weight). Note that the design base shear for this building was 50% of the peak value.
b) At 730 mm roof displacement, a significant soft-storey mechanism was observed at the ground level. At this point, the numerical model became unstable due to global collapse of the ground floor and the simulation was terminated.

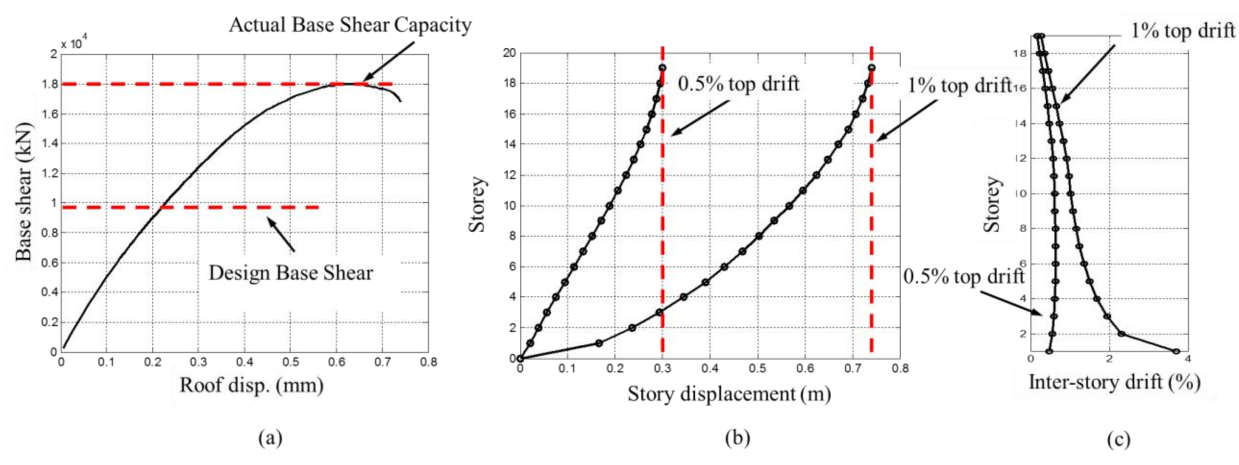

Figure 3.Pushover analysis results: (a) base shear vs. roof displacement, (b) storey displacement, (c) inter-storey drift ratio

Nonlinear response history analysis results with variable friction properties

Nonlinear response history analysis of the building was carried out in the East-West direction using a set of three ground motions from the Pacific Earthquake Engineering Research (PEER) Centre database [22]. The selection of the motions was made in such a way that the mean 5%-damped acceleration response spectrum for the ground motions closely matched the

Maximum Credible Earthquake (MCE_R) spectrum in the selected period range of 0.2T – 1.5T, as suggested by ASCE 7-16 [5], where T is the natural period of the structure in the fundamental mode for the East-West direction. The details of the ground motions are given in Table 1.

Table 1. Input ground motion records

EQ number	Event	Year	Magnitude	PGA [g]	Duration (sec)	Scale Factor
EQ1	Kocaeli_ Turkey	1999	7.51	0.2	28	0.8
EQ2	Kocaeli_ Turkey	1999	7.51	0.17	30	0.6
EQ3	Darfield_ New Zealand	2010	7	0.4	54	0.9

The response history analysis was performed on the fixed-base and the base-isolated building with three different coefficients of friction: 0.08, 0.05, and 0.03. These values are representative of the coefficients of friction of available materials such as PTFE, UHMWPE, and PETP+PTFE sliding against smooth stainless steel surface [8, 9]. The objective was to study the effect of the coefficients of friction of the flat sliders on the global seismic performance of the base-isolated building and confirm the benefits of isolating these types of buildings with the SIP system.

Figure 4 provides the average values of the peak and residual response indicators respectively from the three ground motion events. Based on the obtained results, the following observations are made:

a) For the design level seismic hazard, the maximum inter-storey drift ratio was observed at the first floor of the fixed-based and isolated structures. All inter-storey drifts however were less than 0.5%, which indicates only some moderate damage at the first storey. As the coefficient of friction was reduced from 0.08 to 0.03 for the isolated structures, the inter-storey drift ratio decreased to less than 0.2%. In this study, peak inter-storey drift ratios in the ranges of 0.2-0.5%, 0.5% - 1.5%, and 1.5% - 3% represent damage of drift-sensitive nonstructural components, moderate structural damage, and severe structural damage respectively [23].
b) The maximum absolute sliding displacement increased as the coefficient of friction decreased. The maximum displacement was about 100 mm for the isolated building with 3% coefficient of friction. The behaviour of the isolated building with 8% friction coefficient was similar to that of fixed-base structure. This means that under such ground motion intensity, the isolation system was barely activated and almost all of the seismic energy was transferred to the superstructure.
c) The residual displacement of the isolated superstructure increased as the coefficient of friction decreased from 8% to 3%. This is the major advantage of friction pendulum systems over flat sliding bearings since friction pendulum systems provide adequate restoring mechanism to bring the structure back to its initial location after a severe earthquake.

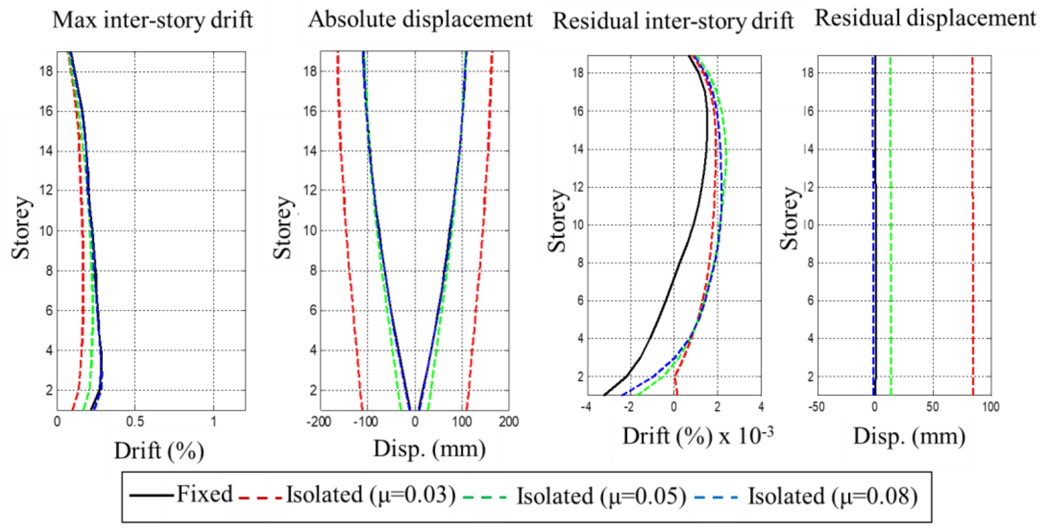

Figure 4. Nonlinear response history analysis results under design level hazard (Mumbai – Zone III)

Response history analysis for higher hazard levels

Once the response history analysis of the fixed-base and isolated building with different coefficients of friction for the zone III (PGA = 0.16 g) was completed, the nonlinear response history analysis of the building, fixed-base and base-isolated with 3% coefficient of friction, for three different Peak Ground Acceleration (PGA) intensities as shown in Figure 5 was performed, representing similar buildings located in higher seismic hazard zones. Same set of ground motions was used in this analysis.

Note that in these analyses, a maximum storey drift ratio of 10% was set as a limit to terminate the simulation. The objective of this study was to investigate the sideway collapse of the building, along with the performance assessment of the isolated-building under different hazard levels and comparing the results with that of the fixed-base building. Figure 6a summarizes the results in terms of the maximum inter-storey drift ratio and residual inter-storey drift ratio. Figure 6b illustrates the average value of columns' axial force variations for the isolated structure during the ground motions due to overturning moments. According to the results:

a) At the highest intensity level (PGA = 0.64 g), the peak storey drift ratio at the first floor for the fixed-base structure was more than 5% which means that severe structural damage requiring the demolition of this building was concentrated at the ground level. The peak storey-drift ratio of the isolated structure was well below 0.5% under all intensity levels, which ensured the functionality of the base-isolated structure.
b) The residual response indicators also showed that the fixed-base structure was severely damaged for the PGA of 0.64g with the residual first storey drift at about 5%, while the residual inter-storey drift ratio of the isolated structure was well below 0.2%. However, the recorded global residual displacement of the isolated structure at the base at this PGA level was 800 mm.
c) Significant variations in the first floor columns' axial forces were observed due to overturning moments in the isolated structure for the PGA of 0.64g. For instance, the axial force in column 1 was initially at 1636 kN; however, this value was varied from 40% to 150% of this initial value. In addition, no uplift was observed in the columns. Such variations are very important to be considered in designing flat sliding bearings since, as mentioned previously, normal stress affects the friction characteristics of such bearings significantly and can cause the deterioration of their friction properties if they are overstressed.

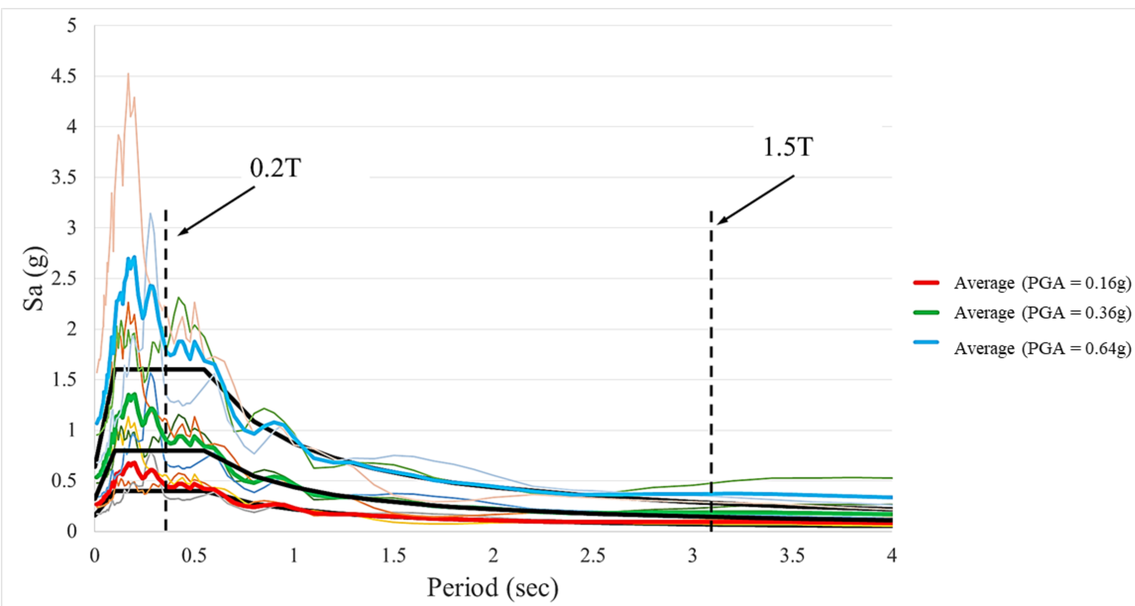

Figure 5. Response spectrum and the median response spectra of the three ground motion records for three hazard levels: (i) PGA = 0.16 g, (ii) PGA = 0.36 g, (iii) PGA = 0.64 g

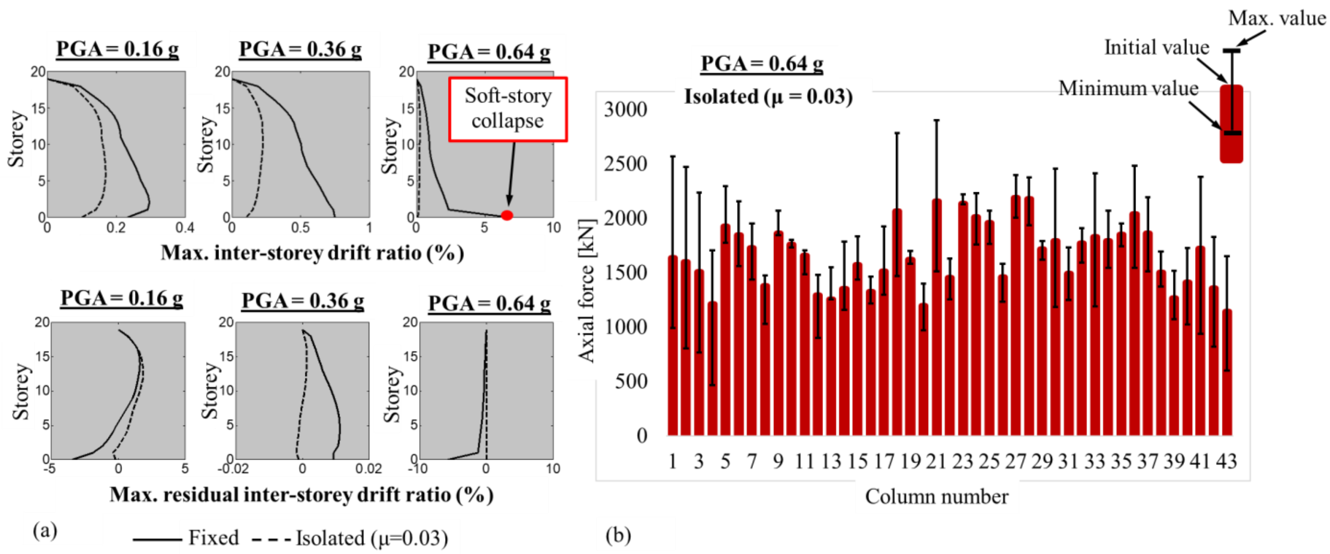

Figure 6. (a) peak global responses resulted from nonlinear response history analysis at three Peak Ground Accelerations, (b) average value of first floor columns' axial load variations for the isolated structure

CONCLUSIONS

This paper presents a cost-effective seismic isolation platform (SIP) concept with simple and low-cost flat sliding isolators that can be mass implemented for the most commonly designed buildings in urban settings in India. The proposed SIP consists of three major sections: the supporting slab, low-cost seismic isolation system, and ground floor columns. The low-cost seismic isolation platform is obtained by "frugalized" flat sliding bearings. A nonlinear finite element analysis of two RC buildings located in Mumbai: (i) fixed-base building, (ii) the same building, but isolated using flat sliding isolation systems was performed to investigate the efficacy of seismic base-isolation systems. The analyses included nonlinear pushover analysis, nonlinear response history analysis using different coefficient of friction values, and nonlinear response history analysis using different PGA intensities. The nonlinear pushover analysis predicted the development of soft-storey mechanism, which was also observed during the nonlinear response history analysis at the PGA of 0.64g. The results of the nonlinear response history analysis at the PGA of 0.64g demonstrated that the peak inter-storey drift ratio was reduced from 6% at the ground floor for the fixed-base structure to less than 0.2% for the isolated structure. The results of the residual inter-storey drift ratio also demonstrated that the base-isolation systems prevented the soft-storey mechanism to be developed as it did in the fixed-base structure. Large residual displacements of the isolated structures were observed in this study. According to the nonlinear response history analysis using different coefficient of friction values, the residual displacement of the isolated structure was increased from 10 mm to 90 mm at 8% and 3% coefficient of friction values respectively. The recorded residual displacement of the isolated structure at the base at the PGA of 0.64g was 800 mm. This indicates the importance of providing adequate space for the displacement of the SIP or providing a re-centering mechanism at the isolation level to reduce the residual displacements. Currently, full-scale component level experiments on a selection of low-cost sliding systems are being conducted at the University of Toronto. Once the experiments are completed, more sophisticated sliding models will be used to model the actual response of the selected low-cost isolator. The supporting slab will also be designed and included in the nonlinear response history analysis of the case study structures. In general, the proposed SIP will provide the means to "frugalize" the currently available robust seismic isolation systems and use them for affordable housing projects in developing countries like India.

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