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A Review Paper on Base Isolators Subjected to Near-Field (NF), Far Field (FF) and Low Frequency Earthquakes

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Abstract: The elastomeric bearing systems are not likely to perform well under near-field and low frequency ground motions. These ground motions contain pulse type and low frequency components respectively. Due to such type of components the horizontal displacement of elastomeric bearing is very high.

The NZ system contains lead core, which adds damping in the system. Due to introduced damping the force deformation behavior of NZ is nonlinear. This will restrict the horizontal displacement of NZ system. But even after this provision the deformation of isolator is quite high. The sliding isolation system may perform better than elastomeric bearing system under near-field and low frequency ground motions as large horizontal displacement of sliding system may not cause failure of the system. However due to lack of restoring force in case of PF, the residual displacement of Pure friction (PF) may be quite high. Frequency pendulum (FPS) has a constant frequency and if the isolator frequency of FPS and excitation frequency match then it may lead to excessive restoring force and corresponding increase in accelerations. The excitation frequency of low frequency ground motion may be from 1s to 2s. Hence the sliding of FPS may be quite high. Ultimately it will introduce higher storey acceleration and base shear. Variable frequency pendulum system (VFPI) has a varying frequency hence it never comes in resonant amplification under any type of excitation. Also due to softening mechanism of restoring force the sliding and residual displacement of VFPI are possibly controlled under near-field and low frequency ground motions.

In conclusion the sliding isolation system is likely to be more effective under near-field and low frequency ground motions.
Keywords: Near-Field, Far Field (FF), low frequency earthquakes, Frequency pendulum, Variable frequency pendulum system.

I. INTRODUCTION

Amongst all the natural hazards, earthquakes have the potential of causing greatest damages. Earthquakes are caused by differential movements of the earth's crust. The result of these movements is well-known 'ground shaking' that can lead to significant damage and/or collapse of buildings, infrastructure systems (e.g. dams, roads, bridges, viaducts etc.), landslides when soil slopes looses their cohesion, liquefaction in sand and destructive waves or 'tsunamis' in the maritime environments.

The purpose of earthquake mitigation of buildings is to provide the structural safety and comfort by controlling the internal forces and displacement within the code specified limits. To improve structural performance of building during earthquake two approaches, conventional and non-conventional are used. In convention approach also known as rigid structure approach buildings are designed to withstand extreme loads produced due to inter storey displacement. In this approach interstory displacements are controlled with the help of addition of shear wall , infill walls and steel braces, use of composite materials etc. In non-conventional approach also termed as flexible structures approach the key parameter is to reduce the excitation forces with the use of dampers and isolators. Structural designer community prefers convention approach over nonconventional due to long-lasting established knowledge and availability of advance technologies relevant to structural stiffening. However, significant interstory drift and floor accelerations of highly stiffened structures raise risks of severe destruction of the building, especially under large scale of earthquake. In addition to this structures which are designed according to seismic codes, the design philosophy adopted in the code is to ensure that structure should posses a minimum strength to resist major earthquake i.e. Maximum Considered Earthquake (MCE) without collapse. This conventional approach of seismic design is not adequate for critical structures such as hospitals, multipurpose halls, power plants and communication centers etc. The effective reduction of interstory drift in the floor can be achieved by base isolation system. Also one can ensure the lowest damage to facilities and also human life.

The Base isolation system was developed in an attempt to mitigate the effects of earthquakes on buildings during earthquake and it is proven effective. Base isolation technique consists of decoupling superstructure from substructure with the help of support mechanism. The isolation systems are made with a) Laminated Rubber (Elastomeric) Bearing. b) Lead Rubber Bearing (LRB) Friction c) Pendulum (FPS) System Bearing.

In nonconventional approach base isolators and base isolated structures were designed for far field earthquakes for Design Basis Earthquake Level (DBE) to remain superstructure in linear state where as isolators in nonlinear state. A primary concern of the base isolated structure is the isolator's displacement and acceleration of the building. In near field earthquakes the structures experiences impulsive type of loading, hence recent year many researches have turned focus towards base isolated subjected to near field ground motions. For near-field ground excitations, even under relatively low frequency earthquake superstructure may get damages and/or total collapse.

Near-field earthquakes (typically within a radius of 20–60 km). Near-field earthquakes are accompanied with two significant effects known as directivity effect and fling-step effect. The direction of rupture propagation relative to the site, forward-directivity, and possible permanent ground displacements, fling step, are the major effects in near fault region. Forward directivity occurs where the fault rupture propagates with a velocity close to the shear-wave velocity (Bhandari et.al.2017). Displacement associated with such a shear-wave velocity is largest in the fault normal direction for strike-slip faults . The fling step is the static component of the near-fault ground motion and is characterized by a ramp-like step in the displacement time-history and a one-sided pulse in the velocity time-history (Agarwal and Shrikhande 2010). Low-frequency earthquake (LFE), a new class of seismic event, was first identified by the Japan Meteorological Agency (JMA) in their seismicity catalog in southwest Japan hypothesized that the reduction of effective stress due to elevated pore-fluid pressure might help promote LFE and tremor generation, and tremors could be considered as a swarm of many LFEs. LFE ground motion is a motion having period ranging between 1 s to 2 s. As the frequency of excitation is low the isolators may be subjected to very high displacement as they may come in the range of dominant frequency. Therefore it is essential to seismic analysis of structure subjected to far field, near filed and low frequency earthquake. (Chi-Chia et.al. 2013).

II. BASE ISOLATION SYSTEMS

The concept of seismic base isolation has been in use for the last several decades, the technology is well developed and there exists a variety of base isolation devices. These devices can be divided into two major groups: elastomeric systems and sliding systems. A brief review of these system is given in this section.

A. Elastometric Bearings

Elastometric devices source their effectiveness from their composite elastomeric material. Resilience is their main advantage. Sometimes service load deformations and durability may be an issue. The common elastomeric devices include: natural rubber bearings, lead rubber bearings etc. The details of the aforementioned devices will be discussed in this section. **(Kamrava 2015).**

1) *Natural Rubber Bearings:* Natural rubber bearings are also known as laminated rubber bearings. They are manufactured of natural rubber or neoprene, a synthetic rubber material employed of its toughness and durability, which has a behavior similar to natural rubber (Kamrava 2015). By alternating rubber and steel shim layers Natural rubber bearings are comprised. With the help of vulcanization process under pressure and heat these layers are joined together to produce a composite bearing. Vertical stiffness to the bearings is provided by Steel shims which prevent the rocking response of an isolated structure. Along with it the steel shims prevent rubber from bulging out under high axial compressive loads. The shims have no effect on lateral stiffness of bearings as it is controlled by the shear modulus of the elastic material. The connection between the foundations and the isolation mat is maintained with help of bearings which are mounted between two thick endplates. Their behavior can also be easily modeled analyzed and hence designed. As natural rubber and neoprene have a consistent shear modulus over time the effects of creep, stiffness deterioration over time are small (Derham et.al. 1985).
2) *Lead Rubber Bearings:* In comparison to natural rubber bearings, lead rubber bearings provide much better capability and adequate stiffness for lateral loads and better damping characteristics. In the lead rubber bearing there is one or more cylindrical lead plugs in the center compared to Natural rubber bearing. The lead plug in combination with the rubber causes the device to demonstrate bilinear behavior. Under low service wind loads, high stiffness of the lead plug attracts most of the load and the arrangement shows high stiffness. Under extreme seismic loads lead is deformed plastically and hence the stiffness of the device drops to just the stiffness of rubber. Lead rubber bearings are also easy to install, manufacture, analyze and design (Kamrava 2015).

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B. Sliding Devices

Elimination of torsional effects in asymmetric structures can be very well achieved by sliding devices. This is because the frictional force utilized in sliding devices is proportional to the axial force on a sliding device due to weight. Therefore, the center of gravity of a building coincides with the center of stiffness of the isolation system thus eliminating torsional effects in asymmetric structures. Pure friction bearings , friction pendulum bearings and Variable Frequency Pendulum Isolator are few advancements of sliding devices (Kunde and Jangid 2003).

1) *Pure Friction Bearings (PF):* Pure friction bearings are the earliest type of sliding devices. They essentially represent a sliding joint, which decouples superstructure from the ground. Under service wind loads the structure behaves like a fixed base building because the load is not sufficient to overcome the static friction force. Under high seismic loads static friction is overcome and the bearing slides. Energy is dissipated in the bearings through friction in the form of Coulomb damping. (Kunde and Jangid 2003).
2) *Friction Pendulum Bearings (FPS):* Friction pendulum bearings combine sliding with pendulum action. The schematic layout of a friction pendulum bearing is shown in Figure 1. They consist of an articulated slider on a spherical concave chrome surface.

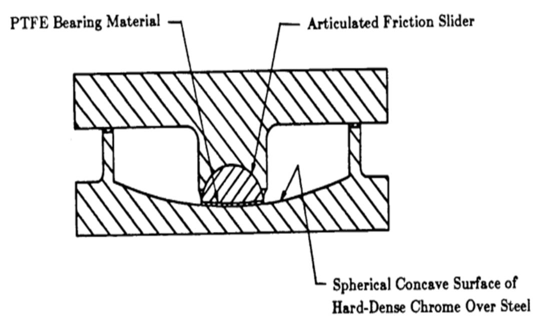

Fig.1. Details of Friction Pendulum Bearings (Zayas V.A. 1990)

The slider is covered with a polished bearing material such as Teflon. The friction coefficient between the surfaces is of the order of 0.1 at high velocity sliding and of the order of 0.05 at low velocities. Just as with the conventional sliding bearings, friction pendulum systems act as a fuse and is activated when earthquake forces exceed the value of static friction. Lateral force developed by such bearings is a combination of frictional force and the restoring force due to the rising of the building up the spherical surface. Furthermore, the lateral force in a particular bearing is proportional to the fraction of building weight supported by that bearing and therefore the center of mass of the building is coincident with the center of stiffness of the support system, which eliminates torsional effects (Zayas V.A. 1990).

3) *Variable Frequency Pendulum Isolator (VFPI):* This is a recently developed isolation system, which combines the advantages and at the same time overrules the disadvantages of both PF and FPS (Murnal and Sinha 2002). As discussed above the limitation of both PF and FPS is due to the geometry of their sliding surfaces. The PF system has true flat sliding surface due to which large sliding and residual displacement are the major problem. On the other hand FPS has spherical surface due to which, under high level of excitation the larger sliding of isolator, which may induces high accelerations in super structure. Hence the golden mean is that the geometry of sliding surface of isolator should not be true flat nor true spherical. This exactly is achieved in VFPI. The geometry of VFPI considered is as shown in Fig.1 (Murnal and Sinha 2002). The geometry of VFPI overrules the limitations of both PF and FPS, while retains the advantages. As shown in the Fig.1 the geometry of VFPI is neither exactly flat nor exactly spherical. Particularly the geometry of VFPI is derived from elliptical shape. This geometry of VFPI is chosen to achieve a progressive period shift at different response levels. The VFPI retains the advantages of both PF and FPS, due to amplitude dependent time period and softening mechanism of isolator restoring force. VFPI is relatively flatter than FPS, which results in smaller vertical displacement for similar sliding displacements. Flatter sliding surface will result in the generation of smaller overturning forces in the structure. If the slider has to have a single point of contact with the sliding surface, the varying radius of curvature does not interfere with smooth movement of the slider. This can be easily achieved in VFPI, hence improving its advantage. Under low level of excitation, the sliding of isolator is also less. It means the sliding of isolator is within central portion of sliding surface. In this situation due to low initial time period, the displacement of isolator is controlled. The restoring force is applied by component of weight of structure acting against sliding. It clearly shows that, the

VFPI behavior is similar to FPS for smaller displacement (with desired high initial stiffness). Under high level of excitation, the sliding of isolator is more but without increase in restoring force. In fact restoring force has a bounded value, which reduces for very high displacements. As a result the force transmitted and input energy transmission in super structure is minimized. At the same time the restoring force, restores the structure close to its initial position. It clearly shows that, the VFPI behaviour is similar to PF system for very large displacement (with large sliding displacement of isolator but without significant residual displacement). As such mainly the geometry of sliding surface will make the VFPI, the most suitable isolator under all levels of excitation.

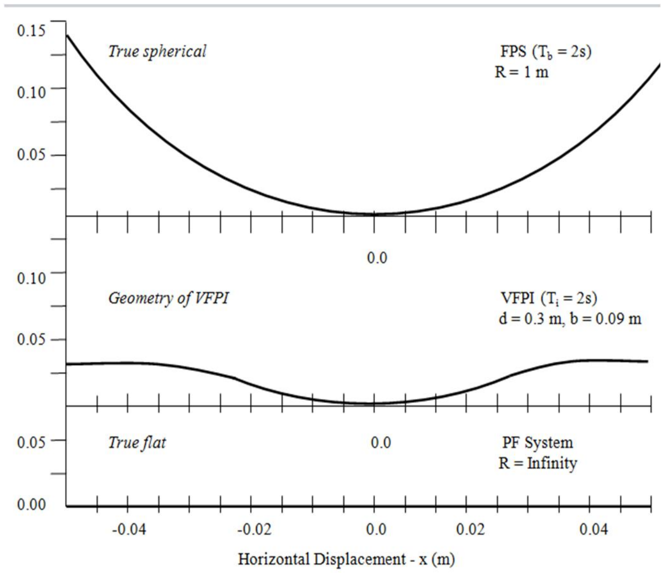

Fig.2 Geometry of Sliding Surface for Various Systems

The main disadvantage of Elastomer and FPS isolator is that, when the frequency of excitation is different than considered in design, the performance of isolator is not satisfactory as these isolators have fairly constant frequency at all displacements. This exactly is overruled in VFPI. The frequency of VFPI is kept varying for its better performance under all levels of excitation. The pendulum effect of isolator will provide necessary restoring force.

C. Base isolators subjected to Near-Field (NF) , Far-Field (FF) and low frequency earthquakes:

The goal of seismic isolation is set as reducing floor accelerations to target limits while keeping base displacements below practical and economical limits. This goal is achieved by (i) elongating the natural period of the building via use of laterally flexible isolation elements this reduces spectral accelerations and thus the effective seismic forces, (ii) allowing the superstructure to move flexibly on the isolation system this provides rigid body motion that minimizes interstory drift ratios, and (iii) providing damping through the isolation elements this helps dissipating the energy input from the earthquake and is particularly essential in limiting the base displacements (Alhan and Seda 2016). The dynamic response of a structure is strongly affected by the characteristics of the earthquake (e.g. intensity, duration, frequency content). At the same time there may be a significant variation in the structural damage potential of a ground motion, for a given earthquake, moving from one site to another. Depending on the combination of parameters like: subsoil conditions, distance from the epicentral area and direction as regards the propagation of the fault rupture. Hence, many representative ground motions need to be considered to develop reliable design response spectra. However, it should be noted that near-fault ground motions, unlike far fault ones, exhibit large incremental velocities which can give rise to large inelastic deformations of the structure regardless of the peak ground acceleration (Anderson and Bertero 1987). Near field earthquakes (typically oriented within a distance of 20–60 km) consist of a major portion of fault energy in the form of pulses. Pulses can frequently be seen in acceleration, velocity, and displacement time histories. These pulses tend to have maximum Fourier spectrum in limited periods, whereas far-field earthquakes have maximum Fourier spectrum in the broad range of periods (Aagarwal and Shrikhande 2010). Near field earthquakes are associated with two significant effects known as directivity effect and fling-step effect. These effects are based on three main active parameters of near-field ground motions, which are rupture mechanism, slip direction of rupture relative to the site, and residual ground displacement.

If the direction of propagation of rupture is aligned toward the site or having a small angle between them and when the velocity of fault rupture is close to shear wave velocity of the site, then it is called forward directivity effect (Aagarwal and Shrikhande 2010). Due to this effect, large-amplitude pulses with the long period (1–1.5 s) and short duration having the high ratio of peak ground velocity (PGV) to PGA (vPG/aPG) are generated, which are highly destructive in nature (Somerville et al., 1997). Fling step effect is accompanied by permanent ground displacement resulting from tectonic deformations. It produces large-amplitude unidirectional velocity pulse and a monotonic step in displacement time history .Apart from this, hanging wall and foot wall effects can be seen in dipping fault earthquakes. These effects have greater influence on acceleration spectra in the short period. Fling step effect mentioned before is the relative slip between the hanging wall and footwall (Bhandari et.al.2017). Near fault ground motions are characterized by long-duration horizontal pulses and high values of the peak vertical acceleration, which can become critical for a base-isolated structure (Mazza et.al. 2012). It is clear that the effects of near fault (NF) ground motions with large velocity pulses can bring the seismic isolation devices to critical working conditions. A nonlinear time history analyses were performed to study the influence of isolation damping on base and superstructure drift. Also various lead-rubber bearing (LRB) isolation systems are systematically compared and discussed for aseismic performances of actual reinforced concrete (RC) buildings. Parametric analysis of the buildings fitted with isolation devices is carried out to choose the appropriate design parameters. The efficiency of providing supplemental viscous damping for reducing the isolator displacements while keeping the substructure forces in reasonable ranges is also investigated. It was concluded that incorporation of additional damping forces makes the structure response ineffective, under moderate or strong ground motions, coming from far fault sites. However Reduction of super structure drift was observed for far-fault base isolated structure. (Providakis 2008). Have investigated the behavior of base-isolated building with the help of a numerical study for far field and near field earthquakes with directivity and fling step effects. Both design-level and extreme level earthquakes. Designated response parameters were peak floor displacement, acceleration, base shear, and isolator displacement. Inelastic behavior of base isolated structure during the earthquake was investigated by performing nonlinear time history analysis of a ten story building frame. Study shows that base isolation was not much effective for near-field earthquakes, even for design level earthquake, the frame gets significantly into inelastic range for earthquakes with fling step effect. (Bhanadari et.al. 2017). A variety of isolation devices including elastomeric bearings (with and without lead core), frictional/sliding bearings and roller bearings have been developed and used practically for aseismic design of buildings. Among the various base isolation systems, the lead rubber bearings (LRB) had been used extensively. Analytical seismic response of multi-storey buildings isolated by lead rubber bearings (LRB) was investigated under near-fault motions by many researchers. An attempt has been made by author to find out optimum yield strength of the LRB which is found to be in the range of 10%-15% of the total weight of the building under near fault motions. The criteria selected for optimality are the minimization of both the top floor acceleration and the bearing displacement. (Jangid 2007). An ample research have been performed experimentally and analytically to study combinations of various base isolation systems. A Rigorous study was performed on base-isolated structures located in a near-fault area, base isolated five-storey r.c. framed buildings with elastomeric bearings acting Base Isolation (BI) system alone or combined in parallel or in series with sliding bearings Base Isolation and in Parallel Sliding (BIPS), or Base Isolation and in Series Sliding (BISS) systems were studied. The adoption of BI, BIPS and BISS systems induced unexpected ductility demand at the end sections of both beams and columns, especially in the lower storeys. It was also suggested that the effects of the horizontal and vertical components of near-fault ground motions should be taken into account (Mazza et.al. 2012). Another attempt was made by (Sharbatdar et.al. 2011), (Providakis 2009) to investigate the seismic response of base-isolated structures with LRB and FPS isolators under near fault ground motions. Parametric study was concentrated on base shear, accelerations and displacements of isolated models. Large displacement and velocity pulses in records of near fault ground motions can significantly change the results of seismic response of base isolated structures. Due to large isolator displacements, buckling may become of significant interest especially when the buckling safety factor is low. Therefore, supplemental dampers alongside the conventional lead-rubber bearings (LRB) or friction-pendulum system (FPS) isolation systems can be incorporated to reduce the isolator displacements in near field earthquake excitations. Also efficiency of providing supplemental damping on FPS base-isolated buildings taking into account.

Many of the existing structures were constructed by using former seismic codes hence it is necessary to evaluate response of existing buildings to near fault ground motions. Idealized pulses were utilized in a study to gain further insight into the effects of high amplitude pulses on structural demands. Findings from this study indicate that near fault records with fling can be more damaging than far fault records but they tend to accentuate first mode behavior. Author emphasized on demands in the fundamental and higher modes must be evaluated by taking into consideration the fact that modal periods shift to the right of the spectrum as the system moves from the elastic to inelastic state (Kalkan and Kunnath 2006).

It is worth to note that influence of regularly distributed masonry infills (MIs), reducing the deformation demand and enhancing the energy dissipation capacity of the bare structure, is not generally taken into account in the seismic assessment of existing buildings (Shing and Mehrabi 2009). Hence More studies are needed to evaluate the effectiveness of the base isolation in seismic retrofitting of reinforced concrete (R.C.) framed structures in the case of masonry infills (MIs) not uniformly distributed in elevation. Failure mechanisms of totally and partly infilled structures were compared by considering three structural models (i) bare structure with nonstructural MIs; (ii) infilled structure with in elevation uniform distribution of structural MIs; (iii) infilled structure with in elevation uneven distribution of structural MIs. From studies it was concluded that regular distribution of MIs is essential in order to obtain a good performance of r.c. framed structure retrofitted with base isolation systems in the near-fault area, because it increases stiffness of the superstructure making base isolation more effective. (Mazza et.al. 2018).

Seismic isolation has proven to be successful under far field earthquakes, its success in case of near field earthquakes is being questioned for over a decade now; due to the presence of long period large velocity pulses. Lowering isolation period and increasing isolation damping aiming to reduce base displacements unfortunately may result in a reduced seismic performance in terms of floor accelerations particularly under far field earthquakes. And the success level of such a precaution under near field earthquakes depends both on the fault-distance and the pulse period to the isolation period ratio. Hence it is very much essential to evaluate the performance limits of buildings equipped with seismic isolation systems of different characteristics when subjected to near field ground motions at different fault distances with different velocity pulse periods. It was shown that optimum isolation system parameters, i.e. isolation period and characteristic force ratio, required to satisfy a performance target in the near field region may suitably be determined via the proposed methodology (Alhan and Seda 2016).

III. CONCLUSIONS

After extensive literature survey it is observed that Base isolators are capable to resist deformations in the case of far-field (FF) ground motions. However, if a structure is located in the vicinity of fault it may be vulnerable to near-field (NF) ground motions. In case of near filed earthquakes structure may experience large durational pluses which can reach peak velocities of the order of 0.5 m/s and durations of 1–3s.

Therefor isolator displacements tend to be considerable in case of NF earthquakes. Hence, isolators with very large dimensions may be required for structures located in NF areas. These costly geometries are in contradiction with the main objective of implementing seismic isolators to reach a more economical and practical solution by decoupling the strong ground motion pulses transferred to the building. Also, low frequency ground motions are motions having period ranging between 1 s to 2 s. As the frequency of excitation is low the isolators may be subjected to very high displacement as they may come in the range of dominant frequency. Hence in recent period it is topic of interest of many researchers and recently several papers for investigating the dynamic behavior of base-isolated buildings under near field and low frequency motion were published. It will not exaggeration to say that very little work has been done in the field of Base isolator subjected to near field and low frequency earthquake.

Moreover, when structure is base isolated with sliding isolators it is essential to study effects of large deformations on its characterization parameters such as friction coefficient and Geometry of sliding isolator etc. Hence, the focus should be given on characterization of base isolators subjected to different type of earthquakes.

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