

History of Passive Sliding Base Isolation Systems

Subjects: [Engineering](#), [Civil](#)

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Base isolation techniques have emerged as the most effective seismic damage mitigation strategies. Several types of aseismic devices for base isolation have been invented, studied, and used. Out of several isolation systems, sliding isolation systems are popular due to their operational simplicity and ease of manufacturing. These isolators behave passively i.e. their properties of independent of frequency of earthquake excitation. Herein, the historical development of passive sliding isolators based on the number of sliding surfaces is discussed.

base isolation

friction pendulum system

multi-surface isolation system

passive isolation system

1. Introduction

Earthquakes are one of the most catastrophic natural events, often resulting in the loss of lives and structures. Humans have been trying to reduce the harmful effects of earthquakes on structures, such as buildings, bridges, and tanks. The main challenge faced in reducing the harmful effect of an earthquake is to arrive at a suitable method to dissipate or offset the vast amount of energy imparted to the structure during a seismic event. In this regard, researchers have been developing some mechanical appurtenances over the years. As a result, several mechanical devices, such as fluid viscous dampers ^[1], visco-elastic dampers ^[2], and yielding-type dampers ^[3], have been invented. Depending on their location and type of arrangement within the structure, these devices absorb seismic energy locally. Over the years, the research focus shifted to developing mechanical devices that can significantly reduce the transfer of seismic energy to the structure, which led to the invention of base isolation systems. In principle, a base isolation system must have very high stiffness in the vertical direction and low stiffness in the lateral direction. High vertical stiffness enables the transfer of gravity loads, whereas low lateral stiffness ensures that the structure behaves as a rigid unit for the lateral load. The main issue to be addressed in the earthquake-resistant design of structures is the resonance problem. During a seismic event, structures generally are prone to frequency amplification as their fundamental frequency typically lies in the range of earthquake frequencies. Base isolation systems minimize the resonance issue by significantly altering the fundamental frequency of the structure.

One of the simplest ways to achieve base isolation is to implement some sliding mechanism between the superstructure and substructure. In its simplest form, this type of isolation can use a sand layer between the superstructure and substructures ^[4]. Although this approach is simple and reasonably effective for small structures,

it is not suitable for multi-story buildings. More recently, Azinović et al. [5] proposed the use of thermal insulation boards installed beneath the foundations of a contemporary energy-efficient building to allow for controlled lateral sliding between the individual layers of the board. Out of the various scenarios considered by these researchers, the sliding prevention scenario was found to be the most cost-effective. To date, several varieties of sliding isolation systems have been developed. These systems are discussed in detail in the subsequent sections. Although the idea of seismic isolation is more than a century old, research and wide practical implementation started about 40 years ago. Since its inception, the concept of base isolation has significantly matured, and various base isolators have been developed, patented, and implemented.

2. Sliding Isolation Systems with a Single Sliding Surface

In Bihar (India), during the 1934 earthquakes, many buildings survived as they developed cracks running longitudinally below the superstructure. These cracks permitted the sliding of the superstructure over the foundation, preventing damage to the superstructure [6]. This observation became the topic of interest, and researchers proposed sliding-type joints [7][8][9][10]. Few authors proposed a pure friction type (P-F) joint, where materials, such as graphite powder, sand or engine oil, are used between the superstructure and substructure to achieve the required coefficient of friction [6][7]. These structures significantly reduced the spectral acceleration when subjected to dynamic loading, indicating the effectiveness of P-F base isolation. Since these studies were restricted to simple one-story buildings, Nikolić-Brzev studied [11] a multiple-level P-F isolation scheme for multi-story buildings. The system was found to be effective in reducing the dynamic response of the buildings when compared with fixed-base buildings. Several other detailed studies and modeling techniques are also available on P-F isolation systems [12][13][14][15][16].

Due to the lack of restoring mechanism in a P-F system, the superstructure may permanently shift from its original position at the end of a seismic event. This residual shift may affect the functional use of the building. Therefore, researchers shifted their focus toward sliding systems with restoring capabilities. Zayas et al. [17] proposed a simple system known as the friction pendulum system (FPS). The isolator consists of an articulated slider, which moves on a stainless-steel spherical surface. The slider is coated with stainless steel and encased in the cavity of a spherical plate. The slider portion in contact with the spherical surface is coated with a composite material with low friction, usually Teflon. Teflon is the trade name of polytetrafluoroethylene (PTFE). During a seismic excitation, the slider moving on the spherical surface may lift the mass, and the gravitational force provides the necessary restoring force. The friction between the slider and surface provides the necessary damping. This type of isolator has been extensively studied, and the results of detailed experimental studies are available [18][19]. Jangid [20] developed a mathematical model for a multi-story building and a bridge isolated with FPS. The researcher found the existence of optimal friction values, which can significantly reduce sliding displacements and floor accelerations. More recently, researchers proposed a regression expression to obtain the optimal value for the coefficient of friction [21]. It was found that the optimal value is dependent on the intensities of earthquakes. Vibhute et al. [22] proposed a graphical approach to obtain the optimal friction value. This method was found to be intuitive and simpler than the optimization algorithms. The effect of local bending effects on the response of FPS isolated

buildings under seismic loading was studied by Tsai [23]. Through the study, the researcher found that ignoring the local bending effect may be unrealistic and should be included in the formulation phase. A study on FPS-isolated structures indicates the importance of considering bi-directional earthquake excitations [24]. It was found that the sliding displacement increases between 20% and 38% in the bi-directional excitation case when compared with unidirectional excitation. Several researchers studied various FPS-isolated structures, such as buildings [25], bridges [26], liquid storage tanks [27], and nuclear power plants [28]. Typically for analysis purposes, FPS is modeled in 1D or 2D; although this is agreeable under normal loading, it is not realistic in extreme loads, which may include uplifting [29]. In this context, several researchers have studied the behavior of FPS under extreme tri-axial loading by considering 3D models [30][31]. It is a well-established fact that the response of a structure is different for a near-fault than for a far-field earthquake. Therefore, base-isolated structures may show large displacements for near-fault pulses [32]. The frequency of an FPS is a function of its sliding geometry alone. Since the curvature of FPS remains the same over the sliding surface, the isolation frequency is constant. As a result, a low-frequency earthquake might induce resonance in the structure resting on FPS. Therefore, Pranesh and Sinha [33] proposed a variable frequency pendulum isolator (VFPI) whose frequency varies along the geometrical surface. The surface considered for the isolator is derived based on the modified expression of an ellipse. Since the curvature changes along the surface, the period of the isolator varies throughout the sliding. As a result, the matching of isolator and earthquake frequency is avoided, effectively curbing the resonance issue. Furthermore, the isolator is found to be effective for high-intensity earthquakes. A similar isolator known as a variable curvature friction pendulum system (VCFPS) was proposed by Tsai [34]. Here, the concave surface of the isolator is derived by subtracting a function from the equation for the sliding surface of FPS. The author studied the effectiveness of VCFPS by considering a numerical model of a building subjected to various earthquakes. The study indicated that the isolator could significantly reduce the base shear even in a near-fault earthquake characterized by low frequency. Lu et al. [35] introduced an isolator with a spherical curvature at the central portion with linearly varying geometry beyond this central region. The isolator is called a conical friction pendulum isolator (CFPI). Due to the geometry, the isolator acts similar to FPS within some threshold, and thus isolation frequency remains constant. Beyond this threshold, the frequency of isolation varies linearly along the geometry owing to the linearly varying surface. A detailed comparison of the FPS, CFPI, and VFPI is given in [36]. Herein, it was found that all the isolators performed well in a far-field earthquake. However, for near-fault earthquakes, VFPI and CFPI are found to be more effective than FPS. Except for FPS, all other isolation systems mentioned earlier have flatter sliding surfaces, resulting in large residual displacements. In an attempt to reduce this residual displacement, Lu et al. [37] developed a sliding isolator known as a polynomial friction pendulum isolator (PFPI). The surface geometry of this isolator is governed by a fifth-order polynomial. The response of PFPI in terms of displacements was significantly lower than FPS for near-fault earthquakes. Krishnamoorthy [38] proposed an isolator whose geometry, as well as the coefficient of friction, varies with isolator displacement, named variable radius friction pendulum system (VRFPS). The geometry of VRFPS varies exponentially along the sliding surface, whereas the coefficient of friction varies linearly along the surface. The isolator was effective for a wide range of earthquake frequencies and significantly reduced residual displacement. Malu and Murnal [39] considered VFPI varying the coefficient of friction along the geometry to reduce the harmful effects of near-fault earthquakes. Rather than linearly varying the coefficient of friction as in VRFPS, the authors varied the coefficient of friction only in two specific regions. Authors claimed that restricting the variation

of friction coefficient only in two regions significantly reduces the difficulties involved in manufacturing these isolation bearings. Moreover, the isolator was effective in reducing both acceleration and displacement. Furthermore, Calvi et al. [40] proposed two more varieties of these isolation systems. One system uses a flat surface known as BowTie (BT), and the other with a curved surface similar to FPS is known as BowC (BC). In both cases, the coefficient of friction varies along the surface. Authors argued that this variable friction coefficient could be practically obtained by creating concentric bands of different materials. Due to the flat geometry, BT lacks the recentering ability, but this could be used as a cost-effective solution for temporary buildings. However, BC has a re-centering capability and thus can be used for more permanent structures. Although analytical studies on BC isolators showed promising results, the authors suggested additional experimental studies to check the practical feasibility of these isolators. The sliding isolation systems generally use costly materials to achieve a low coefficient of friction for the surface. In this regard, a low-cost alternative for typical isolation bearing was suggested by Brito et al. [41]. The isolation system uses typical construction materials, such as concrete and steel, and does not use any replaceable mechanical parts. The authors explored the possibility of combining both convex and concave surfaces for isolation purposes.

3. Sliding Isolation Systems with Multiple Sliding Surfaces

Although the earliest literature on isolators with multiple sliding surfaces dates back to the 19th century [42], a systematic study in this area started only in this century. The effectiveness of sliding isolator systems for a wide range of earthquake frequencies encouraged the researchers to focus on isolators with multiple sliding surfaces. Tsai et al. [43] proposed a multiple friction pendulum system (MFPS) with two concave sliding surfaces. Due to its unique design, this isolator can accommodate large sliding displacements. Furthermore, multiple frictional surfaces provide additional damping, thus offsetting the harmful accelerations. Fenz and Constantinou [44] studied various parameters of double concave friction bearings by varying the coefficient of friction, radii of sliding surfaces, and the height of articulates and sliders. The authors proposed that with several of these variables, designers can arrive at upper and lower isolator surfaces, whose radii can be varied depending on the requirement. Further research in base isolation has led to the development of another multi-stage friction pendulum bearing known as a triple pendulum (TP) bearing [45]. The system makes use of three independent pendulum mechanisms and four concave surfaces. TP bearings are capable of achieving different hysteresis properties when being displaced. This property of variable hysteresis enables the isolator to adapt to different earthquake frequencies. Detailed theoretical and experimental studies of these multi-stage frictional pendulum isolators were carried out by Fenz and Constantinou [46][47]. Since sliding displacements are distributed on all the sliding surfaces, the heat generated during the high-velocity movement is also minimized. Various modeling techniques of these isolators are also available in detail [48][49]. A detailed study has been conducted by Morgan and Mahin [50] to assess the reliability of TP bearings. This probability-based study indicated that TP bearings are effective in various seismic hazard levels. A detailed study of these isolators subjected to extreme forces conducted by Becker et al. [51] showed that the damages are generally limited to inner sliding surfaces. Most recently, Lee and Constantinou [52] developed a quintuple friction pendulum isolator. The isolator has six spherical sliding surfaces, which provides designers with multiple options to achieve complex seismic isolation requirements. A detailed mathematical model and finite

element technique to model this type of isolator are proposed by Keikha and Ghodrati [53] and Sodha et al. [54], respectively.

A comparison of the typical force (f)-displacement (d) behavior and stiffness at various regimes (k) for various sliding isolators discussed to date is shown in **Figure 1**.

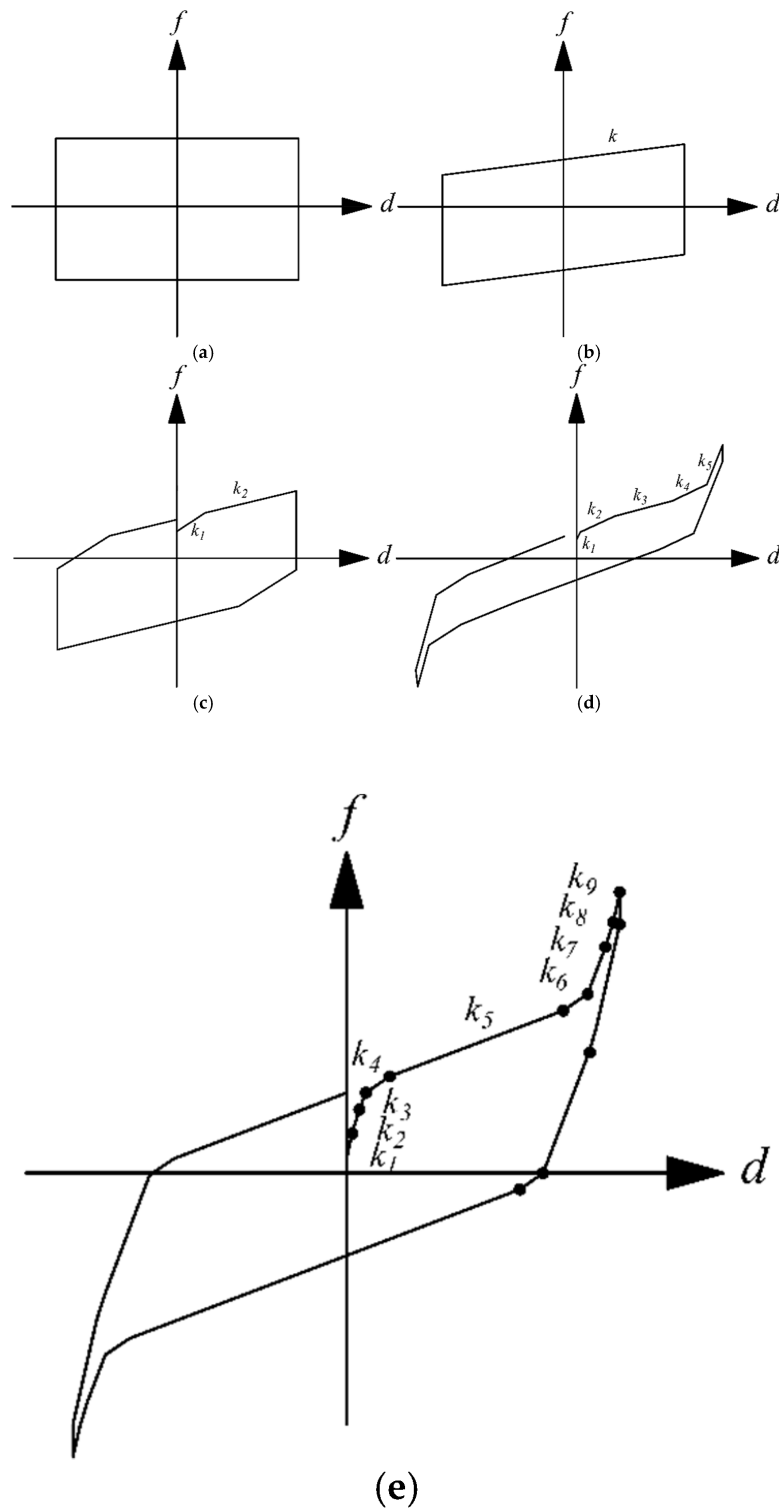


Figure 1. Idealized force-displacement relationship for various isolators. (a) P-F isolator, (b) FP isolator, (c) double concave friction bearing, (d) triple pendulum bearing, (e) quintuple friction pendulum isolator.

As seen in these figures, with the evolution of sliding isolators from single surface pure friction form to quintuple form, plenty of control points are now available to the designers. Each form shows better force-displacement behavior and energy dissipating capabilities than the previous one. At present, with many variables to choose from, the designers can aim at achieving very complex requirements of modern high-rise buildings. Recently, a sliding isolator known as XY-FP is gaining popularity among researchers [55]. The unique feature of this isolator is that it has two different sliding surfaces perpendicular to each other, which permits independent sliding. Due to the arrangement, the isolator can have uncoupled behavior in two directions. Furthermore, the isolator can be designed to have two separate isolation periods by providing different curvatures in each of the directions. This feature benefits designers who wish to address displacement demands in the principal directions. Moreover, due to the vertical connector, this isolator can prevent the uplift, which can be caused by unforeseen vertical accelerations due to earthquakes. Most of the isolators mentioned earlier in this section have curved surfaces which may lead to manufacturing difficulties. In this context, a sloped sliding-type bearing (SSB) has been proposed recently [56]. This isolator has two orthogonal railings similar to XY-FP bearing; however, in contrast to the curved surface, this isolator has two discontinuous slopes. Since the isolator does not have a fixed curvature, it can efficiently avoid the resonance issue. However, this isolator lacks a fillet between two sloping surfaces. As a result, the isolator is prone to impact effects during the transition from one slope to the other.

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