INCREASING THE SAFETY OF STRUCTURES USING BASE ISOLATION

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INTRODUCTION

More than 65% of the land area of India is prone to moderate to severe earthquake shaking, and there are several important infrastructures built in these areas. To safeguard these structures, earthquake resistant design is essential. In contrast to conventional approach of earthquake resistant design, wherein damage is expected to occur in select structural members, the approach adopted in critical infrastructure and important buildings is to eliminate damage to a considerable extent through the use of base isolators. The concept of base isolation is to use base isolators between the foundation and the superstructure, such that the superstructure is isolated from the ground. (This concept is similar to the provision of neoprene bearings at the supports below the bridge decks). Buildings resting on such base isolators are called base isolated buildings. It has been observed from past experience that base isolation systems are more effective for buildings with following conditions: a) stiff superstructure, b) rigid foundation on stiff soil, c) ground motions that do not have sharp pulse-like motions, and d) ductile detailing of the whole structure [IS 1893-Part 6 (2022)].

Seismic isolation systems prevent seismic energy from entering buildings by using devices made from rubber or steel plates coated with a friction-generating material that slide over one another to minimize the effect of an earthquake. These isolation devices are installed between the building's foundation and the building (See Fig. 1). Alternatively, seismic dampers, installed in each story of a building, could absorb earthquake energy the way shock absorbers work in a car and convert it into heat energy to minimize damage.

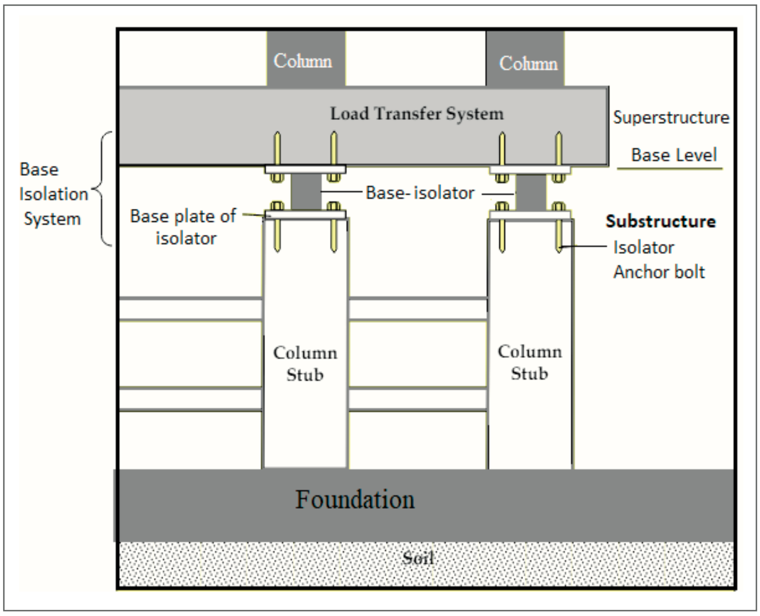

Fig. 1 Sectional elevation of a base isolated building

THE CONCEPT OF BASE ISOLATION

The basic elements of a base isolation system are shown in Fig. 2(a); the supplemental dampers shown are optional and hence may or may not be utilized within an isolation system. These dampers absorb energy and thus increase the damping of the building (Subramanian, 2016). By decoupling the structure from ground shaking, isolators reduce the level of response in the structure that would otherwise occur in a conventional, fixed-base building (see Fig. 2b). Conversely, base isolated buildings may be designed with a reduced level of earthquake load to produce the same degree of seismic protection. Qualitatively, a conventional

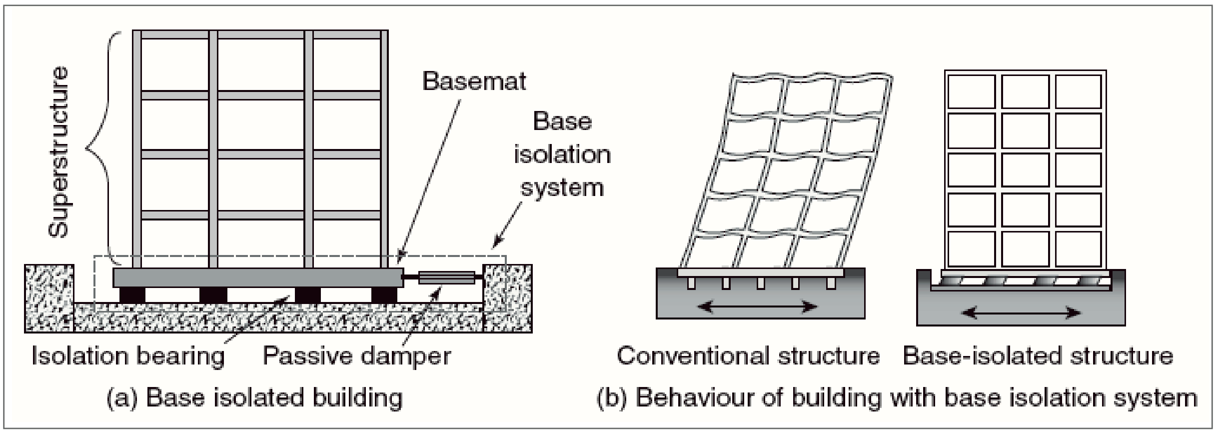

Fig. 2 Concept of base isolation (Source: Subramanian, 2016)

structure experiences deformations within each storey of the structure (i.e., inter-storey drifts) and amplified accelerations at upper floor levels. In contrast, base isolated structures will experience deformation primarily at the base of the structure (i.e., within the isolation system) and the accelerations are relatively uniform over the height of the building.

Typical acceleration design response spectra for three different damping levels are shown in Fig. 3(a). The major effect of seismic isolation is to increase the natural period which reduces the acceleration and thus force demand on the structure. Thus the forces induced by ground shaking will be much smaller than those experienced by 'fixed-base buildings' directly resting on the ground. In terms of energy, an isolation system shifts the fundamental period of a structure away from the strongest components in the earthquake ground motion, thus reducing the amount of energy transferred into the structure. The energy that is transmitted to the structure is largely dissipated by efficient energy dissipation mechanisms within the isolation system.

However, as shown in Fig. 3(b), softer soils tend to produce ground motion at higher periods which, in-turn, amplifies the response of structures having high periods. Hence, seismic isolation systems should not be used in sites with soft soils, such as those present in the Mexico City, where the fundamental natural period of soft soil is found to be approximately 2s. Thus, base isolation systems are most effective on structures built on stiff soil and on structures with low fundamental period (low-rise building); on the other hand they are least effective on structures built on soft soil and on structures with high fundamental period (tall building).

The first structure which used the principle of base isolation is believed to be the Tomb of

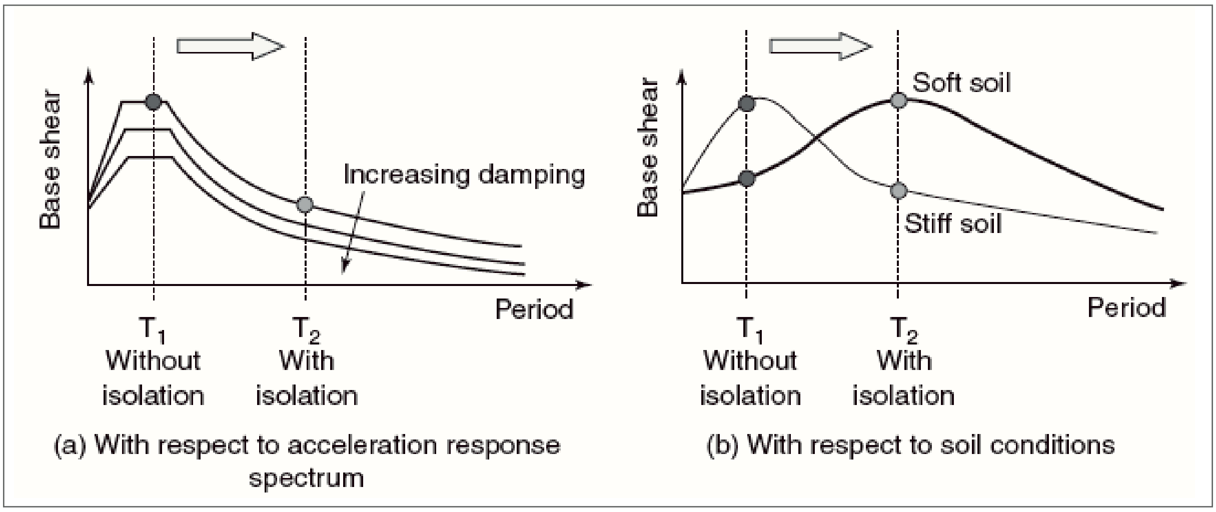

Fig. 3 Effect of seismic isolation (Source: Subramanian, 2016)

Cyrus in Pasargadae, a city in ancient Persia (now Iran) in the 6th century BC. However, the American architect, Frank Lloyd Wright, was the first person to implement some kind of base isolation technique in the Imperial Hotel structure at Tokyo. He provided closely spaced short length piles in the top 2.5 m layer of firm soil that covered a deep deposit of shaky mud. The building survived the devastating 8.3 magnitude 1923 Tokyo earthquake, while other buildings around it collapsed (But eventually the foundation sank irrecoverably into the silt, and the structure was demolished in 1968).

The present day modern base isolation devices started with the pioneering work done by R. Ivan Skinner, W.H. Robinson, and G.H. McVerry at the Physics and Engineering Laboratory of the Department of Scientific and Industrial Research (PEL, DSIR) in New Zealand during 1977 (they used the World's first isolator developed by them in the William Clayton Building, New Zealand) and later by Prof. James M. Kelly at the University of California at Berkeley. The first base isolated building in the United States is the Foothill Communities Law and Justice Center, about 97 km east of downtown Los Angeles. Completed in 1985, the building is four stories high with a full basement and sub-basement for the isolation system, which consists of 98 high-damping elastomeric bearings. The superstructure of the building has a structural steel frame stiffened by braced frames in some bays. Now, more than 1500 structures in the USA have been seismically isolated (www.northernarchitecture.us). The 300-bed district hospital in Bhuj, is the first in India to be installed with 280 lead-rubber and sliding bearings, which was constructed after the Bhuj earthquake in January 2002 (this hospital replaced the one that collapsed tragically in the Bhuj earthquake).

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The first large base isolated building in Japan was completed in 1986. Since the Kobe earthquake, more than 2000 base isolated buildings (many of them apartment blocks) were constructed in Japan. It is estimated that the total number of buildings with seismic isolation in Japan till April 2015 is 7800 (Walters 2015). Base isolation is being adopted in several buildings all over the world. As per Walters (2015) more than 4000 buildings in China have been equipped with base isolators. The application of this technology to multi-storey buildings is also becoming popular, but requires very large isolators.

Isolators of up to 1,600 mm diameter and around 600 mm height are currently available, a size capable of sustaining over 20 MN axial load and 800 mm shear displacement (Nishi et al. 2009). In addition to buildings, seismic isolation has been used for the seismic protection of structures such as bridges, liquefied natural gas (LNG) tanks, and offshore platforms.

The performance of this technology was verified during the 1994 Northridge earthquake of California, USA, the 1995 Kobe earthquake of Japan, as well as the 2008 Sichuan earthquake of China. For example, a California hospital remained operational, unlike other conventionally built structures in the area (Nishi et al. 2009).

TYPES OF BASE ISOLATION SYSTEMS

Many types of isolation system have been proposed and have been developed to varying stages, with some remaining only in concepts and others having installed in several projects. Fig. 4 shows the various types of base isolation systems; they may be broadly classified as (a) elastomeric bearings (lead-rubber bearing, high-damping natural rubber bearing, low-damping natural or synthetic rubber bearing, low damping natural rubber with lead core), (b) sliding bearings (flat sliding bearing, spherical sliding bearing, friction pendulum systems), (c) sliding/friction bearing, (d) rolling systems (using cylindrical rods or elliptical bearing), and (f) combined systems (examples are the Électricité de France system used in nuclear power plants in France and the resilient-friction base isolators). Some of the frequently used isolator systems are shown in Fig. 5.

The Elastomeric bearing is the most common type of base isolation device, and consist of alternating rubber and thin steel plates layers (about 3 mm thick), firmly bonded to each other (Figs 5a and 5b). The bearings are constructed by placing un-vulcanized rubber sheets and steel shims in a mold, then subjecting the mold to elevated temperature and pressure to simultaneously vulcanize and bond the rubber. The steel plate reinforcement provides a high compressive stiffness to reduce vertical deflection under the heavy weight of the structure, making the isolator stable. The rubber layers provide the very low horizontal stiffness needed to give the structure a horizontal natural frequency (typically 0.5 Hz), lower than the peak frequencies of an earthquake (Nishi et al. 2009). This decouples the structure from ground shaking, reducing the transmission of earthquake forces into the structure and protecting both the structure and its contents (50–85% reduction has been achieved). In addition, a rubber cover is provided on the top, bottom, and sides of the bearing to protect the steel plates. In some cases, a lead cylinder is installed in the center of the bearing to provide high initial stiffness and a mechanism for energy dissipation.

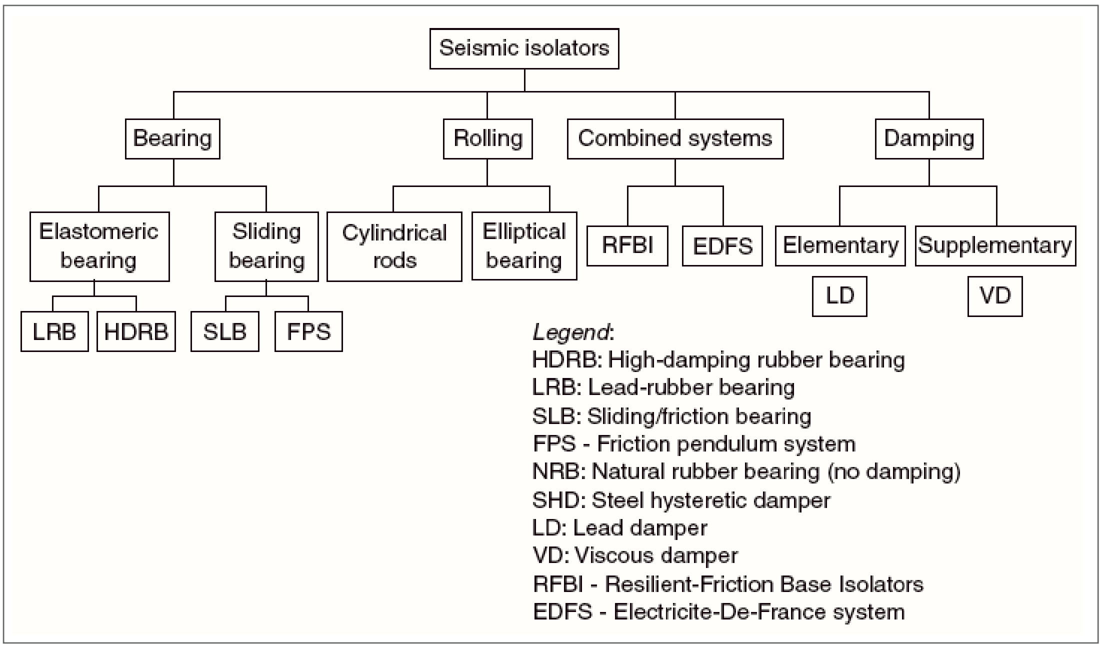

Fig. 4 Types of seismic isolators (Source: Subramanian, 2016)

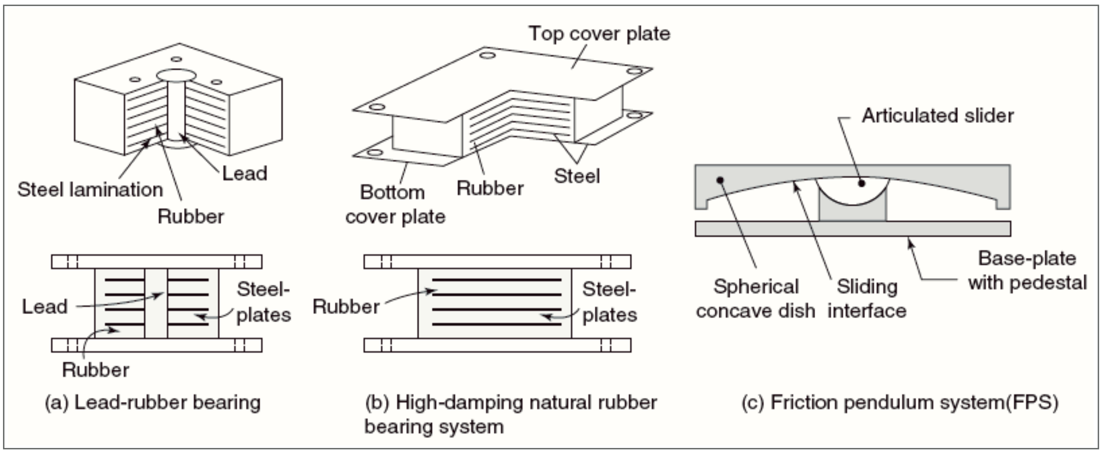

Fig. 5 Common types of seismic base isolators (Source: Subramanian, 2016)

The Lead-rubber bearings (LRB) were first introduced and used in New Zealand in the late 1970s. They differ from low-damping natural rubber bearings only by the addition of a lead-plug that is press-fit into a central hole in the bearing. The lead-plug deforms plastically under shear deformation, enhancing the energy dissipation capabilities compared to the low-damping natural rubber bearing (see Fig. 5a). After the lead yields, it dissipates energy as it is cycled. Fatigue of the lead is not a concern since lead recrystallizes at normal temperatures. During a large earthquake, a shear (horizontal) displacement of several hundred millimeters may be imposed on the isolators. The rubber layers provide the large shear deformation capacity needed. The service life of the isolators is anticipated to be at least several decades.

Sliding bearings typically utilize either spherical or flat sliding surfaces. The friction pendulum system (FPS) bearing utilizes an articulated slider that moves horizontally on a spherical dish-shaped surface and is used extensively in the United States. Usually, the sliding surface is oriented concave down to minimize the possibility of debris collecting on the sliding surface (see Fig. 5c). The articulated slider is faced with a Teflon coating. Under horizontal motion the spherical concave dish displaces horizontally relative to the articulated slider and base-plate. Friction between the PTFE type material and stainless steel surface provides frictional resistance and energy dissipation, whereas the radius of curvature of the spherical concave dish provides a restoring force. The most recently developed triple friction pendulum version of FPS, patented and manufactured by Earthquake Protection Systems, Inc., contains a compound articulated slider with multiple sliding surfaces to allow control of the sliding sequence and the resulting hysteresis curve (Walters 2015).

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Mayes et al. (2012) compared the cost-benefit analysis of isolated and non-isolated buildings and concluded that considering the cost of earthquake insurance premiums, using base isolation without earthquake insurance can be a more cost-effective solution than a conventional fixed based structure with insurance, despite the high cost premium for base isolation.

PERFORMANCE OF BASE ISOLATED BUILDINGS IN THE 2023 TURKEY & SYRIA EARTHQUAKES

On Feb. 6, 2023 at 4:17 am local time, a 7.8-magnitude earthquake struck near the city of Kahramanmaraş, Turkey, as a result of complex fault rupture with a total length of about 400 km. Nine hours after that, a second 7.5-magnitude earthquake struck again, 60 miles north of the first one, with a total fault rupture of about 190 km. This sequence of shallow earthquakes together with their numerous aftershocks caused widespread devastation, killing over 50,000 people and with more than 200,000 building collapsing or heavily damaged over a vast region in southern and central Turkey (Sönmez et al., 2023).The modern reinforced concrete design specification in Turkey (TS 500) was enacted in 2000. This state-of-the-art code mainly resembles ASCE 7 for the design of new buildings and follows ACI 318 code clauses. However most of the buildings that collapsed are pre-2000 buildings which were more vulnerable to earthquakes due to the inadequacy of the older seismic design code, the lack of construction inspection, and poor quality of materials used (Sönmez et al., 2023).

These earthquakes also tested advanced building technologies that were used to minimize damage and keep buildings functioning after a quake. Several hospitals built with seismic isolation system survived the earthquakes with almost no harm, according to local news reports, even while surrounding buildings sustained heavy damage. For example, the Adana City

Hospital, Sown in Fig. 6, survived the earthquake without damage. It also had instrumentation to record both ground shaking and the building's response. Thanks to its seismic isolation system, the building saw a 75% reduction in shaking, according to the company that designed the isolation system, compared with neighboring structures. This system allowed this hospital building to stay up and running during and after the earthquake. Ref. 14 provides the details of the ten largest base isolated buildings in the world.

Fig. 6 The Adana City Hospital in Turkey with a seismic isolation system helped it to stay up and functioning during and after the earthquake (Source: Ref.13)

SOME PROBLEMS OF CURRENT BASE ISOLATOR SYSTEMS

It has to be noted that normal base isolation systems provide only horizontal isolation and are rigid or semi-rigid in the vertical direction. A rare exception to this rule is the full isolation (horizontal and vertical) of a building in southern California isolated by large helical coil springs and viscous dampers (Kircher 2012). The implementation of the base isolation requires optimal design, which depends on the magnitude and frequency range of the earthquake that is being considered. Recent research reveals that the base isolation system may be vulnerable for buildings situated in the near-fault and far-fault earthquakes zones. Near-fault earthquakes with a large displacement and long-period pulse, such as the 1994 Northridge earthquake, may lead to over-stretching of isolator and resulting in malfunctioning of the system (Jangid and Kelly 2001). While far-field earthquakes (with its low-frequency components falling into the resonant region of the conventional base isolation system) may result in amplification of destructive responses to the protected structures.

INDIAN CODE ON BASE ISOLATION

Several codes have been developed for the specification and design of seismic isolation devises such as AASHTO (2014), EN 15129:2018R, ISO 22762-1 (2018), ISO 22762-3 (2010), and ISO 22762-4 (2014).The Bureau of Indian standards issued the code IS 1893 (Part 6) Criteria for Earthquake Resistant Design of Structures: Part 6 Base Isolated Buildings in February 2022. This standard provides guidelines for the estimation of design lateral force and displacement to be considered in the design of buildings with base isolation system, method of structural analysis to be adopted in the analysis of such buildings and guidelines for testing of the seismic isolation devices that are used in such buildings. According to this standard, the base isolated buildings are expected to perform better than conventional fixed base buildings, during moderate to severe earthquakes. As per this code, ductile detailing of the whole structure is necessary, even in base isolated buildings. This standard may also be used for the design of base isolation system for existing buildings, as part of earthquake retrofitting. In such cases, full dynamic analysis has to be done to determine the performance of the building.

As per this code, base isolated building should be designed considering seismic zone, site characteristics, vertical acceleration, gross cross-section properties, occupancy,

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configuration, structural system, and height as per IS 1893 (Part 1). Base isolated buildings should be located at sites that have Soil Types I and II as classified in IS 1893 (Part 1). Additionally, even where Soil Types I and II are found, it should be ascertained that there is no possibility of liquefaction. All base isolator units should be firmly anchored to the substructure and the superstructure. The forces in the connecting elements should not exceed their design strength as per IS 800 for structural steel members and as per IS 456 for reinforced concrete members.

The code does not allow any tensile load in any base isolation device. When tensile loading occurs, the maximum tensile stress should be restricted to the shear modulus of the base isolator. Additionally, in such cases the response history analysis should be used (including the effect of vertical component of earthquake forces). The factor of safety against overturning at the base of the substructure should not be less than 1.4 and that against sliding should not be less than 1.2.

Only regular buildings as per IS 1893 (Part 1) should be attempted to have base isolation. In addition, the centre of resistance along two horizontal plan directions of the base isolators should coincide with the centre of resistances of the substructure as well as the super structure. Services and utilities that cross the isolation interface should be designed and detailed to accommodate the total displacement without disruption in their functionality.

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SEPARATION FROM THE ADJACENT BUILDING AND LOCATION OF MOAT

The wall of the moat of a base isolated building should be placed at a distance not less than the total design displacement Δ_{ID} of the base isolator units, estimated as per clause 6.1.4 of IS 1893-Part 6. When two base isolated buildings are adjacent to each other, the minimum clear distance between them should be equal to the sum of the design displacement plus two times the total lateral displacement of each building, estimated as per clause 6.1.8 of IS 1893-Part 6. A base isolated building should be separated from an adjacent building (whether base isolated or not) by a distance greater than the design displacement Δ_{ID} plus the separation distance specified in clause 7.11.3 of IS 1893 (Part 1).

LOCATION OF BASE ISOLATORS

All base isolators in a building should be placed at a single level such that their top levels are in the same horizontal plane. When isolators are placed on column stubs, the maximum height of the column stubs below the isolators shall not be more than 2.5 m. It is required to have adequate space for inspection, both during installation and later for replacement of these base isolator units. In addition, it should be ensured that the base isolators are protected adequately in case of fire, flooding or freezing.

METHODS OF ANALYSIS

The IS 1893 (Part 6) code allows both the equivalent static method, and the response spectrum method for the structural analysis of base isolated buildings to arrive at the design lateral displacement and the design lateral force of the isolation system. However, while using the equivalent static method all of the following conditions should be satisfied:

- The building is not located within 20 km from any known active fault;
- The building rests on Soil Type I or Soil Type II, as per IS 1893 (Part 1);
- It has a height of 20 m or less above the base level;
- The effective natural period T_{eff} of the building is less than 3.0 s;
- The effective natural period T_{eff} along the considered direction of shaking is more

than three times the fundamental natural period T of the corresponding fixed-base building;

- The base isolation system meets all of the following three criteria: (1) Its effective stiffness at the design displacement is more than one-third of its effective stiffness at 20 percent of the design displacement; (2) It is capable of re-centering after the earthquake; and (3) It possesses force-displacement characteristic independent of the rate of cyclic loading.
- The structure is located in Seismic Zone II only; and
- The structure conforms to the configuration regularity criteria as per IS 1893 (Part 1).

Due to these restrictions, it is always preferable to use the response spectrum method for the structural analysis. The IS 1893-Part 6 code may be referred for the other clauses pertaining to the use of the response spectrum method. In addition, the IS 1893-Part 6 code also specifies several full-scale testing of select samples of base isolators. In addition, the code mandates that two test isolators, similar to those used in any project should be kept at the site and subjected to the same environmental conditions. The test isolators should be tested after 15 years of installation and then 3 years thereafter to check the impact of aging and deterioration on the mechanical properties.

More information on seismic base isolators, analytical and numerical models, other code provisions for seismic isolation, buckling and stability of isolators, design examples, computer applications, and recent trends may be found in Kelly (2012), Kircher, 2012, Naeim and Kelly (1999), Skinner et al. (1993), Walters (2015), and Zhou and Xian (2001).

SUMMARY AND CONCLUSIONS

In contrast to conventional approach of earthquake resistant design, wherein damage is expected in select structural members, the approach adopted in critical infrastructure and important buildings is to eliminate damage to a considerable extent through the use of base isolators. Base isolators are passive structural control systems, and are installed between the building's foundation and the super-structure.

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By decoupling the structure from ground shaking, isolators reduce the level of response in the structure that would otherwise occur in a conventional, fixed-base building. Base isolated structures will experience deformation primarily at the base of the structure (i.e., within the isolation system) and the accelerations are relatively uniform over the height of the building. It has to be noted that seismic isolation systems may not be effective on sites with soft soils or on structures with high fundamental period (tall building). The American architect, Frank Lloyd Wright, was the first person to implement some kind of base isolation technique in the Imperial Hotel structure at Tokyo. The first use of modern base isolated devices was in the Foothill Communities Law and Justice Center, near downtown Los Angeles. The 300-bed district hospital built in Bhuj during 2002 is the first in India to be installed with 280 lead-rubber and sliding bearings.

The various types of base isolation systems may be classified as (a) elastomeric bearings, (b) sliding bearings, (c) sliding/friction bearing, (d) rolling systems and (f) combined systems. Out of these systems, the elastomeric bearing is the most common type of base isolation device, and consist of alternating rubber and thin steel plates layers firmly bonded to each other.

The effective performance of these base isolators have been demonstrated during the 1994 Northridge earthquake, USA, the 1995 Kobe earthquake of Japan, the 2008 Sichuan earthquake of China, and the recent 2023 Turkey & Syria Earthquakes. It has to be noted that normal base isolation systems provide only

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horizontal isolation and are rigid or semi-rigid in the vertical direction. Several codes have been developed for the specification and design of seismic isolation devises. The salient clauses in the recent Indian code, IS 1893-Part 6 (2022) on base isolated buildings have been indicated. It is seen that the use of these base isolators will be beneficial, in spite of their high initial cost, especially in critical infrastructure such as bridges and hospitals.

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