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BASE ISOLATION SYSTEMS

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Abstract

Base isolation (BI) is one of the most widely accepted techniques of structural control to protect structures from strong earthquakes. It is introduced to decouple the building structure from potentially damaging earthquake motion preventing the superstructure absorbing the earthquake energy. In this project, base isolation systems are reviewed and their history, types, purposes and main principles are discussed.

The research aims to study the effect of using base systems consisting of cross linear bearings and rubber bearings in improving the seismic behavior of tall buildings under the influence of several earthquakes, using the ABAQUS program, by changing several parameters (change of building height, friction coefficient within the cross linear bearing, damping energy of rubber isolators accompaniment).The mechanism of the base isolator increases the natural period of the overall structure, and decreases its acceleration response to seismic motion.

Keywords :BASE , ISOLATION, SYSTEMS.

1-1 Introduction

Earthquakes represent one of the most dangerous natural hazards. Base isolation (BI) systems have emerged as a crucial technology for enhancing the reliability of structural systems during an earthquake. At present, Base Isolation-also referred as Seismic Isolation (SI), is the most promising method to lessen the effects of the major earthquakes. The SI technology is still considered new; therefore, its usage is limited, and can be utilized worldwide. In addition to the important results of the theoretical and experimental research, is genuine effectiveness was confirmed by the ideal performances of the isolated structures struck by the severe earthquakes in Los Angeles, California in 1994 (3,4).

Normally, a building is supported directly on its foundations, and it is said to have a fixed-base. When base isolation is used, special structural bearings are inserted between the bottom of the building and its foundation. Seismic isolation bearings are structural joints that are installed between a structure and its foundation support columns. The purpose is to minimize the damage caused by large lateral displacements observed during earthquakes. These bearings are not very stiff in the horizontal direction, so they reduce the fundamental frequency of vibration of a building.

Unfortunately, the base isolation approach cannot always be applied to retrofit the existing structures. The likelihood of its application primarily relies on upon the actual configuration of the existing old structures, particularly when their construction has been progressively modified with the expansion of irregular components.

In addition, the retrofitting works required by the utilization of the base isolation systems might be extremely costly. For example, frequently the floors at ground level are sporadically connected over a huge area and at some point they rest directly on the soil. Hence, the use of a base isolation system requires the construction of a new floor and a new foundation. Then again, when the base isolation system can be reasonably connected underneath the foundation level, it ensures a very effective seismic execution. The fitting isolating system can be directly related to the actual seismic capacity of the current structure. So, no fortifying works of the structure are required over the isolating interface. In principle the seismic performance, contingent upon the characteristic period, can be designed to withstand any level of seismic force. In practice, the design limitations depend on the sidelong displacements that the structure can undergo under the seismic forces.

If the earthquake has frequencies with high energy that match the natural frequencies of the building, it will cause the building to oscillate violently in harmony with the earthquake frequency. However, if the natural frequency of the building can be changed to a frequency that does not coincide with that of earthquakes, the building is less likely to fail.

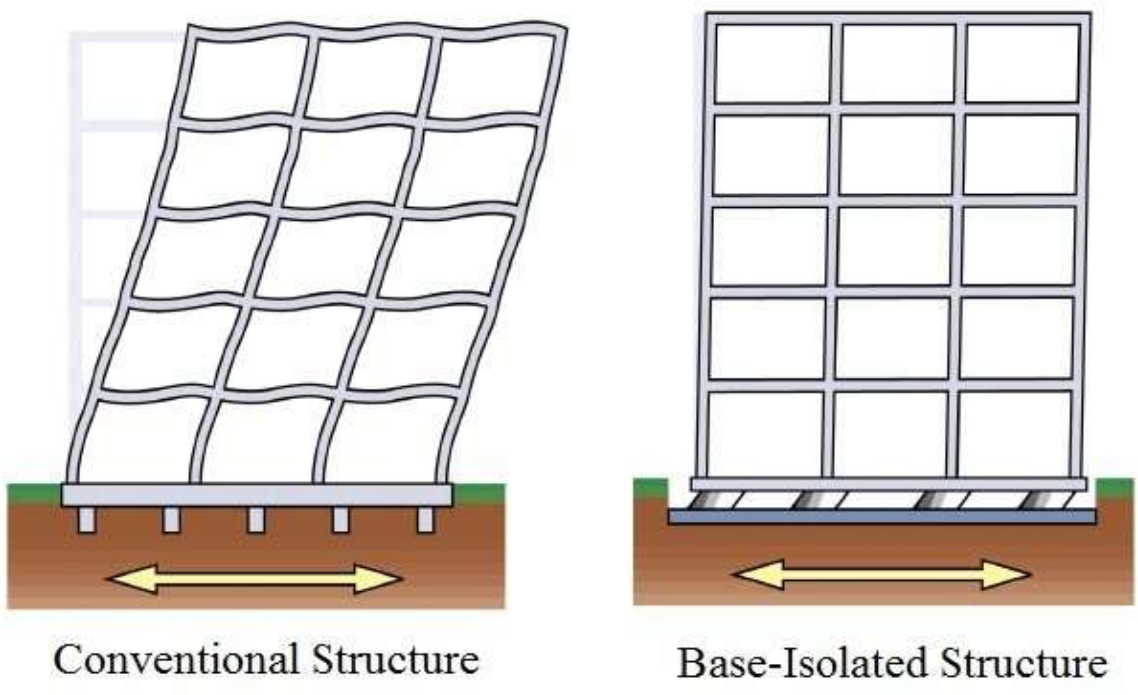


Figure (1.1) comparison of base-isolated and conventional structures

1-2 The concept of base isolation

The main feature of the base isolation technology is that it introduces flexibility into the connection between the structure and the foundation. In addition to allowing horizontal movement, the isolators

are often designed to absorb energy and thus add damping to the system. This helps in further reducing the seismic response of the building. In the strict sense, the structure (i.e, a building or a bridge) is separated from its foundation. The term base isolation, is becoming supplanted with seismic isolation nowadays, indicating that sometimes the separation is some place over the base. For instance, in a bridge the superstructure might be separated from substructure columns. In another sense, the term seismic isolation is more accurate in any case in that the structure is separated from the effects of earthquake (5).

All things considered, in a quake, the ground moves and it is this ground movement which causes a large portion of the harm to structures. A plane flying over a tremor is not influenced. Along these lines, the rule is straightforward. isolate the structure starting from the earliest stage. The ground will move; however, the building will not move. The main way a structure can be bolstered under gravity is to lay on the ground. Isolation clashes with this basic design prerequisite (5).

In this way, nobody has solved the problems associated with perfect isolation systems and they are probably not going to be solved soon. Meanwhile, seismic tremors are causing damage to structures. These systems work to give a compromise between connection to the ground to resist gravity and partition starting from the ground to resist seismic excitation.

Base isolation falls into a general category of passive energy dissipation, which also includes in-structure damping. In-structure damping is added by damping devices within the structure to dissipate energy but does not permit base displacement.

1- 3 Loads Affecting Structures

The determination of the loads acting on a structure is a complex problem. The nature of the loads varies essentially with the architectural design, the materials, and the location of the structure. Loading conditions on the same structure may change from time to time, or may change rapidly with time.

Loads are usually classified into two broad groups: dead loads and live loads. Dead loads (DL) are essentially constant during the life of the structure and normally consist of the weight of the structural elements. On the other hand, live loads (LL).such as the weight of occupants, snow and vehicles. usually vary greatly the magnitudes of these loads are not known with great accuracy and the design values must depend on the intended use of the structure.

In structural analysis two kinds of loads are generally used: 1) distributed loads that act over a surface area.(most loads are distributed or treated as such), and 2) concentrated loads that are single forces acting over a relatively small area.

1-4 Earthquake Characteristics

An earthquake is sudden ground movement caused by the sudden release of energy stored in rocks. Earthquakes happen when so much stress builds up in the rocks that the rocks rupture. The energy is transmitted by seismic waves. Earthquakes can be so small that they go completely unnoticed, or so large that it can take years for a region to recover.

The reduction in acceleration response when the period is lengthened is a result of the characteristics of earthquake motions. In spite of the fact that we generally approach structural design using earthquake displacements or accelerations, it is the velocity that highlights the effects of isolation best. The energy input from an earthquake is proportional to the velocity squared.

1-5 History Of Base Isolation

In spite of the first patents for base isolation were in the 1800's, and cases of base isolation were claimed amid the mid 1900's (e.g. Tokyo Supreme Lodging), it was the 1970's before base isolation moved into the mainstream structural engineering. Isolation has been used on bridges from the mid 1970's and structures from the late 1970's. (12).

Base isolation is one of the most powerful tools of earthquake engineering pertaining to the passive structural vibration control technologies. It is meant to enable a building or non-building structure to survive a potentially devastating seismic impact through a proper initial design or subsequent modifications. In some cases, application of base isolation can improve the structure's seismic performance and its considerably.

The lead rubber bearing (LRB) was developed in the 1970's and this permitted the flexibility and damping to be included into a single unit. About that time the first applications using rubber layers for isolation were constructed. These bearings had the downside of minimal damping and were not sufficiently stiff to resist the loads (12).

Advancements in rubber technology in the early 1980's lead to new rubber compounds which were termed "high damping rubber" (HDR). These compounds delivered bearings that had a high rigidity at low shear strains however a lessened rigidity at higher strain levels. The first building and bridge applications in the U.S. in the mid 1980's used either LRBs or HDR system (12).

The sliding bearings used parallel with LRBs or HDR system in some early activities, ordinarily to support light segments, for example, stairs. Sliding layers were not used alone as the isolation system. Although they have large levels of damping, they do not have a reestablishing force. A structure on sliding bearings would likely end up in an alternate area after a seismic tremor and keep on dislocating under aftershocks.

2 -The Base Isolation System

2-1 BASE ISOLATION

Base isolation, also referred as seismic base isolation or base isolation system, is a standout amongst the most prevalent methods for supporting a structure against earthquakes. It is a gathering of auxiliary components which ought to significantly decouple a superstructure from its substructure laying on a shaking ground; therefore, securing a building or non-building structure's integrity (10).

Buildings respond to earthquake ground shaking in different ways. When the forces on a building or the displacements of the building exceed certain limits, damage is incurred in different forms and to different extents. If a brittle building is designed to respond elastically with no ductility, it may fail when the ground motion induces a force that is more severe than the building strength. On the other hand, if the building is designed to have ductile behavior, it will be damaged but will still be able to weather severe ground shaking without failure.

As mentioned above, some alternatives to avoid significant damage in buildings in strong ground shaking are:

1. To provide the building with unreasonably high strength (which may not be economically justified).
2. To design the building to have a normal (economically justifiable) strength following damage resistant principles; in this case despite the seismic force being larger than the building strength damage will be minimal and restricted only to easily replaceable sacrificial components.

3. To alter the building's characteristics through external intervention such that even in strong ground shaking the demand is less than the design strength of the building and its components.

2-2 Construction Method for Base Isolators

Base isolation is a diverse structural design technique applied to buildings and bridges located in severe seismic areas. Many structures are being built by making use of this technique, while many others are in the design stage or under construction. Almost all the finished buildings and those under construction utilize rubber isolation bearings in the isolation system.

Lead rubber base isolators comprise of three essential segments –a lead plug, rubber, and steel, which are for the most part put in layers shown in Figure (2.4) (10) .

Rubber: The rubber gives flexibility through its capacity to deform and come back to its original position. Toward the end of an earthquake, if a building has not come back to its original position, the rubber layer will slowly bring it back. This may take months, but it will come back to its original position.

Lead: The lead was chosen because of its plastic property, while it might deform with the movement of the quake, it will return to its original shape, and it is equipped for moving ordinarily without losing quality. Amid an earthquake, the kinetic energy of the quake is ingested into heat energy as the lead is distorted.

Steel: Used layers of steel with the rubber means the bearing can move in horizontal direction but is very stiff in vertical direction.

2- 3 Approaches for Base Isolation System

In the classification of structural control, base isolation is a passive control technique. To accomplish the execution of base isolation, passive devices, including dampers and isolators, can be joined into the structures. The isolation system gives the parallel adaptability and the damping important for effective isolation, and builds up the proper stiffness that is required for the service load (6) and the base-isolated building. Acceleration is decreased as the base isolation system decrease the building's natural period, which is the time required for to move away and then return to its original position during free vibration. The classification of typical isolators is shown in Figure (2.1) (6)

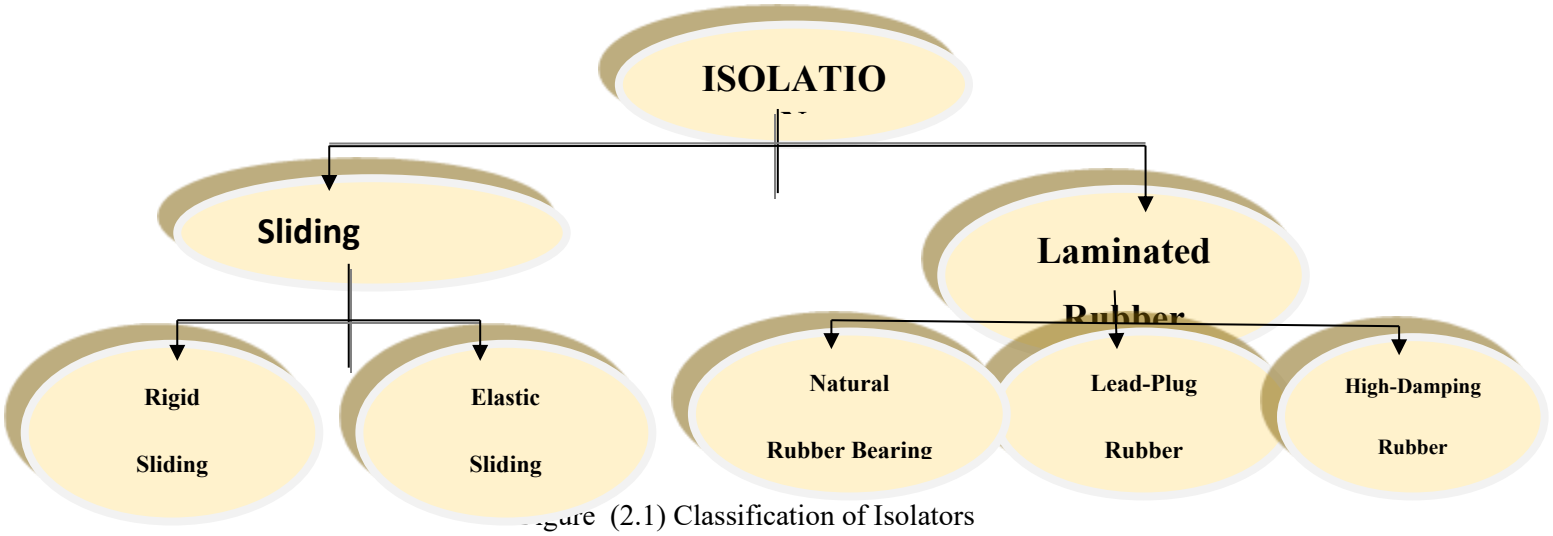


Figure (2.1) Classification of Isolators

2-4 Types of Base Isolators

Many types of isolation have been proposed and produced as described in the following sections:

2- 4-1 Elastomeric Base Isolation Systems

Elastomeric bearings are shaped of horizontal layers of synthetic rubber in thin layers bonded between steel plates, as shown in Figure (2.2). The steel plates keep the rubber layers from bulging thus the bearing can bolster higher vertical loads with just small deformations. Under lateral loads, the bearing is flexible (10,6).
The rubber in the building seismic isolator (lead rubber bearing), acts as a spring. It is very soft laterally but very stiff vertically. The high vertical stiffness is achieved by having thin layers of rubber reinforced by steel shims. These two characteristics allow the isolator to move laterally with relatively low stiffness yet carry significant axial load due to their high vertical stiffness. The lead core provides damping by deforming plastically when the isolator moves laterally during an earthquake.
Plain elastomeric bearings give flexibility but no noteworthy damping. Strategies used to overcome these deficits incorporate lead centers in the bearing.



Figure (2. 2) Elastomeric Bearing

2-4-1-1 Low-Damping Rubber Bearing

In this type of rubber bearings are used in conjunction with supplementary damping devices, such as, viscous dampers, steel bars, frictional gadgets, et cetera. The elastomeric used as a part of bearings may be natural rubber or neoprene. The isolators have two thick steel endplates and many thin steel shims. The rubber bearing comprises of layers of 5-20 mm thick rubber, vulcanized between steel shims. The rubber layers give the bearing its generally low shear stiffness in the

horizontal plane while the steel plates control the vertical stiffness furthermore determine the most extreme vertical load, that can be applied safely. The steel plates also prevent the bulging of the rubber, as shown in Figure (2.3) (10) .
A standard rubber block can be easily compressed and sheared because of its biaxial softness. A laminated rubber bearing can be easily sheared, but its high vertical stiffness allows it to support a heavy structure such as a building.



Figure (2. 3) Rubber bearing and its shear deformation

2-4-1-2 High Damping Rubber Bearings (HDRB)

High damping rubber bearings (HDRB) are ideal for seismic isolation. They are vertically stiff, capable of supporting vertical gravity loads, while being laterally flexible, capable of allowing large horizontal displacements. In effect, the building is allowed to remain stationary while the ground moves back and forth during an earthquake, The HDRB bearings are flexible and have energy absorption capability. The rubber bearings isolation system partly reflects and partly absorbs some of the earthquake input energy. Significant reductions in structural and non-structural damage can also be attained through the use of HDRB rubber bearings seismic isolation.
Damping ratios range somewhere around 8% to 20% of critical. The shear modulus of high-damping elastomers, typically ranges between 0.34 MPa and 1.40 MPa. The material is nonlinear at shear strains under 20% and exhibits higher stiffness and damping, which minimizes the reaction under wind load and low-level seismic load .
Over the range of 20-120% shear strain, the modulus is low and consistent. At large shear strains, the modulus and energy dissipation increase. This increase in stiffness and damping at large strains can be exploited to produce a system that is hardened for the low input, is genuinely flexible at design level input, and can constrain displacements under unexpected input levels that surpass design levels (10) .

2- 4-1-3 Lead-Plug Bearings (LRB)

Lead-plug rubber bearings were developed in New Zealand in 1975. The system of lead-plug rubber bearings is fundamentally the same as that of low-damping natural rubber bearings. As shown in Figure (2. 4), there are three fundamental bits of equipment-layers of steel plates, rubber layers and lead core (10) **.**

A lead rubber bearing is a much larger laminated bearing manufactured from layers of rubber which are sandwiched together with layers of steel and in the middle of the bearing there will be a solid lead "plug." Top and bottom of the LRB is fitted with steel plates, which are used to attach bearing to building through its foundation. Lead rubber bearings are designed in a way that the bearing is stiff and strong in vertical direction and flexible in horizontal direction. Lead, inserted as center of LRB, dissipates the energy of earthquake, and the rubber, reinforced with steel plates, helps in providing stability, supports structure and isolates vibrations.

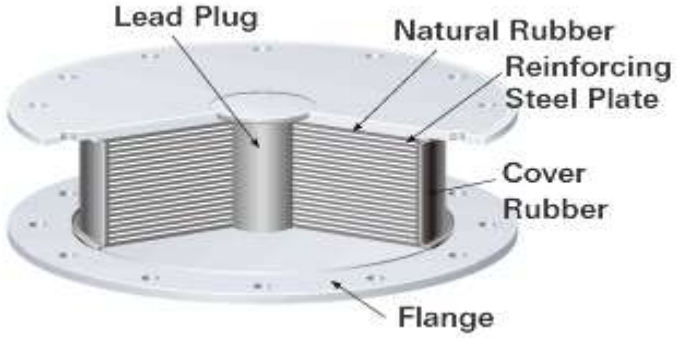


Figure (2.4) Components of Lead-plug rubber bearing

2-4-2 Sliding Base Isolation Systems

Sliding isolator works based on the principle of friction. The lower the friction coefficient, the less the shear is transmitted. In sliding isolator, two pure flat stainless steel plates, or a spherical surface and an articulated friction slider slide over each other during the earthquake excitation. For initiation of sliding the intensity of exciting force must be more than frictional force of isolator. Hence during earthquake excitation, the frequency of which is not harmonic, the isolator displacement is of stick-slip nature.

A sliding base isolation system is considered to be a less demanding system shown in Figure (2.6) and, furthermore, the basic concept of a sliding system is to decrease floor accelerations at the expense of shear displacements between the foundation and the upper structure. It can be accomplished by introducing the friction.

A few studies (References 7 and 8) have pointed out that small masonry structures cannot be isolated cost effectively utilizing elastomeric isolators. In this manner, sliding systems have become more economical alternatives to elastomeric base isolation systems.



Figure (2.5) Sliding Base Isolation System

2-4-2-1 Spherical Sliding Base Isolation Systems

Base isolation generally involves introducing components which are horizontally flexible to allow lateral displacement, but vertically stiff to safely carry gravitational loads (i.e, static weight of structure). The horizontal flexibility increases the period of the structure which lowers peak acceleration levels during an event. A fixed-base building (built directly on the ground) will move with the ground motion and can have extensive damage as a result. When a building is isolated from the ground, resting on flexible bearings or pads known as base isolators, it will only move a little or not at all during an earthquake.

In the spherical sliding base isolation systems, the building is supported by bearing pads that have a curved surface and low friction. During an earthquake, the building is free to slide on the bearings. Since the bearings have a curved surface, the building slides both horizontally and vertically.

According to the (References 7 and 8), the forces wanted to move the structure upwards limiting lateral forces the which would some way or another cause structure deformations. Likewise, by adjusting the radius of the bearings curved surface, this property can be utilized to design bearings that also lengthen the structure, natural period of vibration. As of late, the spherical sliding system (FPS) has become a widely accepted device for seismic isolation of structures. The idea is to isolate the structure from ground shaking during the strong earthquake. Seismic isolation like the friction pendulum bearing is designed to lengthen the structure's natural period far from the dominant frequency of the ground motion and to dissipate the vibration energy during an earthquake .

The properties of the sliding surface materials are key for the execution of the isolation system. The friction pendulum bearing consists of a spherical stainless steel surface and a slider, covered by a Teflon-based composite material. During a strong ground motion, the slider moves on the spherical surface lifting the structure and dissipating energy by friction between the spherical surface and the slider. This isolator uses its surface curvature to generate the restoring force from the pendulum action of the weight of the structure on the friction pendulum bearing. Figure(2. 6)

shows the typical cross section of friction pendulum bearing base isolator and the motion of friction pendulum bearing (7).

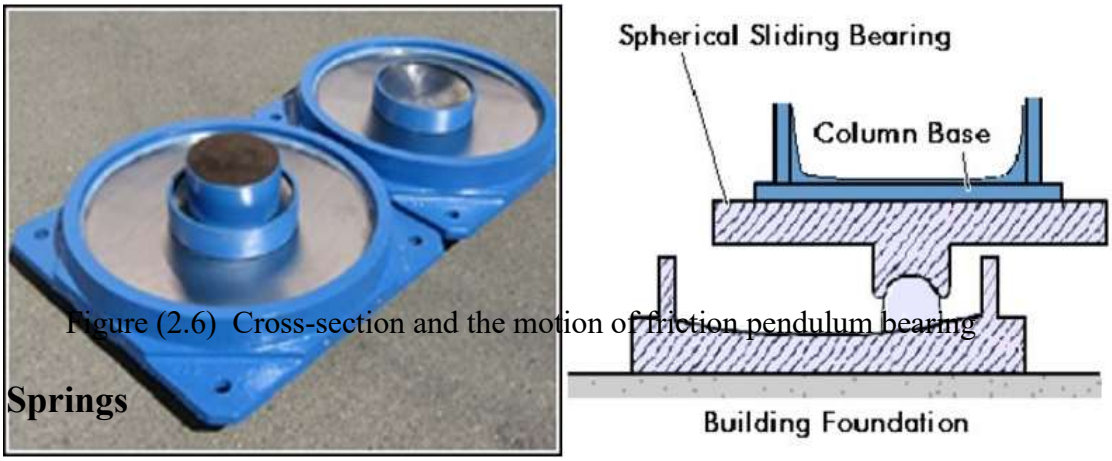


Figure (2.6) Cross-section and the motion of friction pendulum bearing

2-4-3 Springs

Steel springs are another type of isolation devices. They are not broadly used, and their most likely application is machinery isolation. The principle disadvantage with springs is that most are flexible in both the vertical and the horizontal directions. The vertical flexibility will permit a pitching reaction. Springs alone have small damping and move unreasonably under service loads (6).



Figure (2.7) Cross-section of spring

2-4-4 The Purpose of Base Isolation

A high extent of the world is subjected to earthquakes and people expect that structural engineers will design the structures with the goal that they can survive the effects of these earthquakes. The wind and earthquake are the most predominant loads that demand lateral strength of a structure. Earthquake load is not controllable and it is not practical to design a structure for an indefinite seismic demand. The inertial forces caused due to earthquake is directly proportional to the mass of structure and the ground acceleration. Increasing the ductility of the building or increasing the elastic strength of the structure is the most conventional method of handling seismic demand. Engineer has to increase the capacity to

ensure it is higher than the demand. Base isolation takes an opposite approach, it aims to reduce the seismic demand instead of increasing the capacity. Controlling the ground motion is impossible, but the demand on structure can be modified by reducing the motions being transferred from the foundation to the structure.

2-5 The Isolation Demand and Capacity

The earthquakes happen and they are uncontrollable events . In that sense, it is necessary to acknowledge the demand and make sure that the capacity of the structure exceeds it. The seismic the causes inertia forces acting on the building mass. As the ground accelerations increase, the strength of the building, the capacity, have to be increased to avoid structural damage (5).

2-5-1 Dampers used in Base Isolation Systems

Commonly used dampers in base isolation systems are listed below, and also shown in Figure (2.8).

1) Steel Dampers
2) Oil Dampers
3) Lead Dampers
4) Friction Dampers with disc springs



1) Steel Dampers



2) Oil Dampers



3) Lead Dampers



4) Friction Dampers with disc springs

Figure (2.8) Dampers used in Base Isolation Systems

2-5-2 Advantages of Base Isolation

The advantages of base isolation can be listed as follows:
1- Reduction of the seismic demand on the structure, thereby reducing the cost of structure.
2- Lesser displacements in the structure during an earthquake.
3- Improvement in safety of structures
4- Reduction of the damages caused during an earthquake. This helps in maintaining the performance of the structure after the seismic event.
5- The performance of structure is enhanced under seismic loads.
6- Preservation of property.
7- The base isolation ensure that superstructure avoids the structure by avoiding plastic deformation and demonstrates elastic behavior during and after the excitation of the base.
8- Higher protection of the non-structural elements of the structure
9- Base isolation can be retrofitted to appropriate existing structures; however, an excessive number of factors need to be considered.

2-5-3 Disadvantages of Base Isolation

The disadvantages of base isolation can be listed as follows:

1) Not effective at high-rise buildings.
2) Inappropriate for structures built on soft soil.
3) Difficult to implement effectively.
4) It cannot be applied partly in the structures unlike other retrofitting.
5) Allowance for large base displacement is required.

3- THE PRINCIPLE

3.1 Principle of Base Isolation

The basic idea of base isolation is to change the behavior of the building so that the ground can move without transmitting these movements into the building. In a perfect system, this partition would be total. Presently, there should be some contact between the building and the ground (5).
If the earthquake has frequencies with high energy that match the natural frequencies of the building, it will cause the building to oscillate violently in harmony with the earthquake
frequency. However, if the natural frequency of the building can be changed to a frequency that does not coincide with those of earthquakes, the building is less likely to fail. This is exactly what a base isolator does.
The base isolator reduces the stiffness of the structure and thereby lowers its natural frequency. In this condition, the building's superstructure respond to the vibrations as a rigid unit instead of resonating with the vibrations. Simply put the building's foundation moves with the ground and the base isolator flexes to reduce the transmission of the ground motion to the superstructure .

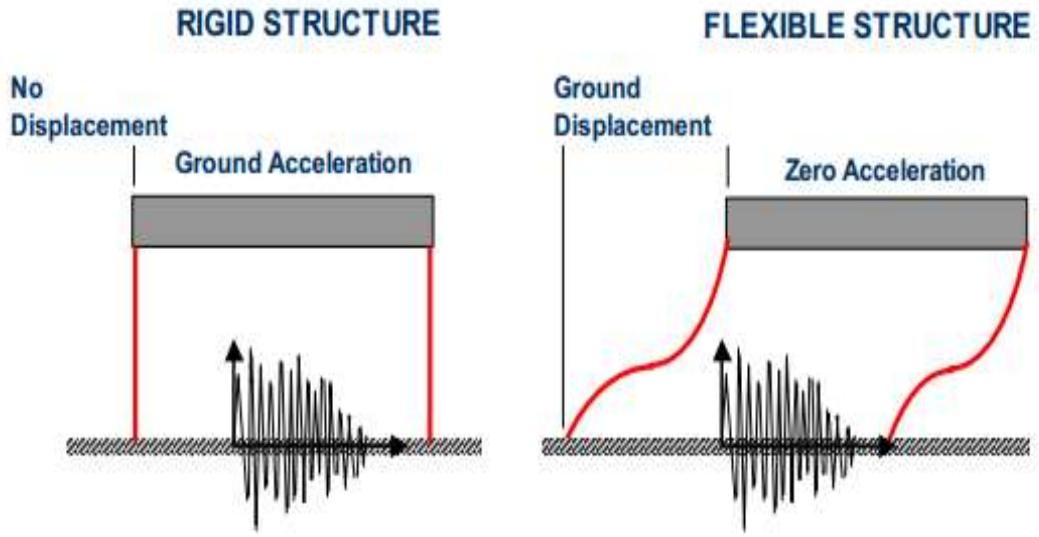


Figure (3.1) Transmission of ground motion

3-2 When to Use Isolation

The simple answer is when it provides a more effective and economical alternative than other methods of providing for earthquake safety. The first criterion to consider obviously relates to the level of earthquake risk– if the design for earthquake loads requires strength or detailing that would not otherwise be required for other load conditions then base isolation may be viable. When we evaluate structures which meet this basic criterion, the best way to assess whether the structure is

suitable for isolation is to step through a check list of items which make isolation either more or less effective (5).

3.2.1 Period of the Structure

The most appropriate structures are those with a short natural period, less than about 1 second. For buildings, that is usually less than 10 stories and for flexible types of structure, such as steel moment frames, probably less than 5 stories (5). practical isolation systems shift the period to the 1.5 to 3.5 second range. If the structure is already this range of period, not much benefit will be obtained from isolation, although in some cases, energy dissipation at the base.

3.2.2 Weight of the Structure

Most practical isolation systems work best with heavy masses. As we will see, to obtain effective isolation we need to achieve a long period of response. The period is proportional to the square root of the mass, M, and inversely proportional to the square root of the stiffness, K:

To achieve a given isolated period, a low mass must be associated with a low stiffness. Devices that are used for isolation do not have an infinite range of stiffness. For example, elastomeric bearings need to have a minimum diameter to ensure that they remain stable under seismic displacements. This minimum plan size sets a minimum practical stiffness.

Sliding systems do not have this constraint and so low weight buildings may be able to be isolated with sliding systems.

However, even these tend not to be cost effective for light buildings for different reasons. Regardless of the weight of the building, the displacement is the same for a given effective period and so the size of the slide plates, the most expensive part of sliding bearings, is the same for a heavy or a light structure. In real terms, this usually makes the isolators more expensive as a proportion of first cost for light buildings.

There have been systems proposed to isolate light buildings. However, the fact remains that there are few instances of successful isolation of light structures such as detached residential dwellings.

3.2.3 Subsoil Condition

Isolation works best on rock and stiff soil sites. The soft soil has a comparable effect to the basin type conditions mentioned above, it will change the seismic waves so that there is an increase in long period motion compared to stiff sites. Soft soil does not preclude isolation in itself; however, the effectiveness will be decreases (5).

3.2.4 Seismic Conditions Causing Long Period Waves

Some sites have a travel path from the epicenter to the site ;thus, the seismic motion has a long periodic motion. This case most frequently occurs in sedimentary basins and can cause resonance in the isolated period range. Isolation may make the reaction worse, not better in these situations. Examples of this type of motion have been recorded in Mexico City and Budapest (5).

3.2.5 Configuration of the structure

The configuration of the structure is the most important item to consider if the dynamic characteristics and site conditions are convenient for isolation. Base isolation requires a plane of separation, where large horizontal offsets occur during the earthquake. These displacements (often

termed the “rattle” space) might range from under 100 mm in low and average seismic zones up to 1 meter or more in high seismic zones near a fault. Allowance for these displacements must be included in the design of the isolation system.
For new structures, this is not generally a problem though the maximum clearance available may impose a restraint on the design of the isolation system. It will rule out the retrofit of structures that nearly abut other structures (5).

4- SELECTION OF ISOLATION PLANE

4-1-1 Selection of Base Isolation in Structures

A key requirement for the installation of the isolation system is that the building be able to move horizontally relative to the ground, usually less than 100 mm, and in some cases up to one meter. A plane of separation must be specified to allow this movement.

4-1-2 Isolator installation techniques

The most common configuration is to install a diaphragm immediately above the isolators. This permits earthquake loads to be distributed to the isolators according to their stiffness. For a building without a basement, the isolators are mounted on foundation pads and the structure is constructed above them Figure (4.1).

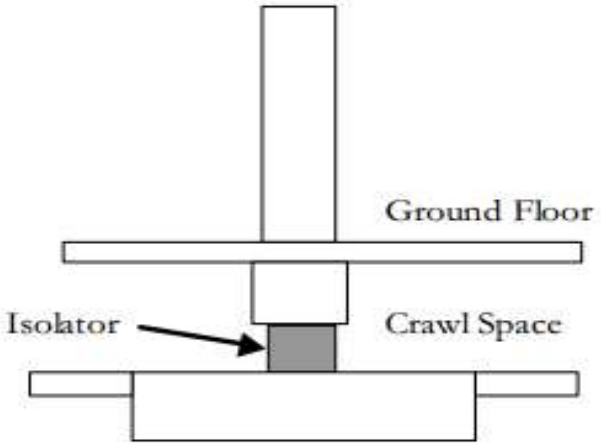


Figure (4.1) Building with no basement

If the structure has a basement, consequently the options are to install the base isolation at the top, bottom or middle of the basements columns and walls, as shown in Figure (4.2). For the options at the bottom or top of the column/wall consequently the component should be designed for the cantilever moment developed from the maximum isolator shear force. This will usually require considerable column sizes and might require plasters in the walls to resist the face loading .

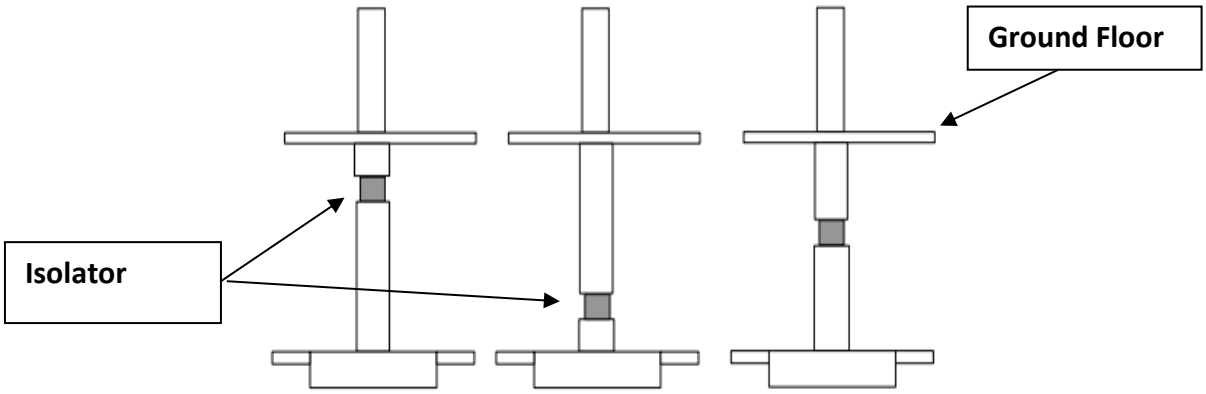


Figure (4.2) Installation in basement

4.2 Bridges

The position for the isolation plane for bridges is at the top of bents, isolating the superstructure as shown in Figure (4.3). The pier will work as a cantilever if the bents are single column bents. Multiple columns bents will work as cantilevers under longitudinal loads but will act as frames transversely if the isolators are put above the top transverse beam.



Figure (4.3) Multiple and single column bents

4.3 Other Structures

For other types of structures, selection of the isolation plane will follow the same general principles as for buildings and bridges. Isolation decreases the inertia forces in all mass above the isolators, so the general aim is to isolate as much of the weight as possible, which usually means placing the isolators as near to the base as possible. Exceptions may be where a large mass is supported on a light frame, such as an elevated water tank. It may be possible to install the isolators under the tank at the top of the frame. This will isolate the majority of the mass and will minimize the overturning moments on the isolators, avoiding tension loads in the isolators. But, the frame base must be able to resist the overturning moments from the maximum isolator shear forces applied at the top of the frame.

The structures considered within these guidelines, buildings, and bridges are all relatively heavy, and most isolation devices are generally suited to large loads. This is because for a given isolation period the displacement is the same regardless of the mass, and it is hard to retain the stability of small isolators under large displacements.
Sliding devices function well under light loads and there has been some improvement work performed on other low mass devices. Systems based on elastomeric bearings are appropriate for loads per device of at least 50 KN(preferably 200 KN), which may restrict their use in structures other than buildings and bridges.

5- DESIGN PARAMETERS AND COMPARATIVE ASSESSMENT

5-1 Dynamic Behavior of Isolated Structures

The response of a base-isolated structure can be understood from the simplified lumped-mass models shown in Figure (5.1). In the fixed-base model the floor masses are connected to the ground only through the flexible columns, so the ground motion is transmitted almost unchanged to the upper floors. In the isolated model an additional layer of isolators, with stiffness K_b and damping c_b, is placed between the foundation and the superstructure. Because this layer is much more flexible than the superstructure, most of the lateral displacement is concentrated in the isolators and the superstructure moves approximately as a rigid block (5,10,17).

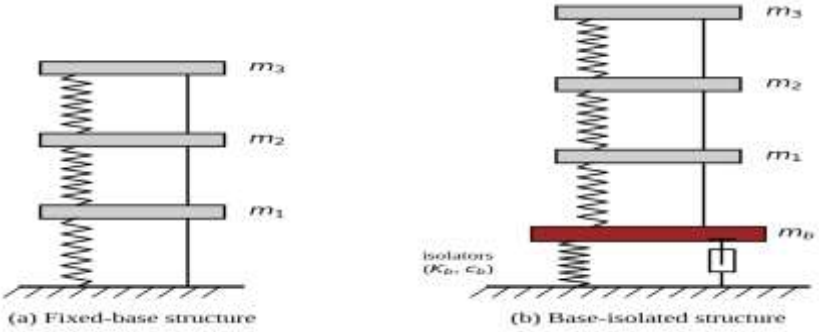


Figure (5.1) Simplified lumped-mass models of (a) a fixed-base structure and (b) a base-isolated structure

For a single-degree-of-freedom idealization, the natural period depends on the supported mass M and the lateral stiffness K, as stated in Section 3.2.2 (18):

$$T = 2\pi \sqrt{\frac{M}{K}} \tag{5.1}$$

Equation (5.1) shows that the period of an isolated structure is lengthened by lowering the effective stiffness of the isolation system. As an illustration, Table (5.1) gives the effective stiffness required to obtain several target periods for a structure with a weight of 10,000 kN (mass of about 1,020 tonnes). Shifting the period from 0.5 s to 3.0 s requires the lateral stiffness to be reduced by a factor of 36, because stiffness varies with the inverse square of the period.

Table (5.1) Effective stiffness required for a target period (W = 10,000 kN)

Period T (s)	Required K (MN/m)	K / K(T = 0.5 s)	Remark
0.5	161.0	1.000	Typical fixed-base building
1.0	40.3	0.250	Upper limit of short-period structures
2.0	10.1	0.062	Lower end of isolated range
3.0	4.5	0.028	Mid isolated range
4.0	2.5	0.016	Very flexible isolation system

Source: calculated by the author from Equation (5.1), $K = 4\pi^2 M/T^2$.

The ability of the isolation system to dissipate energy is described by its force-displacement hysteresis loop, idealized in Figure (5.2) as a bilinear curve defined by the characteristic strength Q, the post-yield stiffness K_d and the elastic stiffness K_1. These parameters are typical of lead rubber bearings (16,17) and of sliding bearings, where Q is governed by the friction force. For a maximum displacement D, the effective stiffness and the equivalent viscous damping ratio are obtained from Equations (5.2) and (5.3) (10,13):

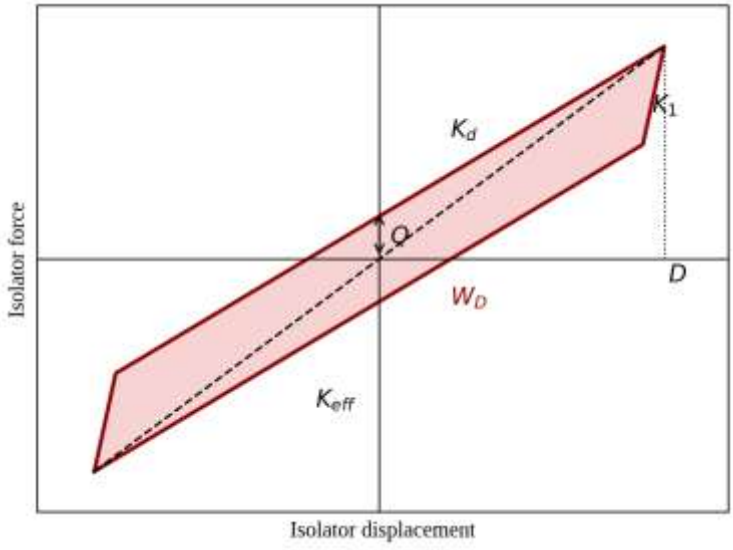


Figure (5.2) Idealized bilinear force-displacement relationship of an isolator

$$K_{\text{eff}} = \frac{F^+ - F^-}{\Delta^+ - \Delta^-} \tag{5.2}$$

$$\beta_{\text{eff}} = \frac{W_{\text{D}}}{2\pi K_{\text{eff}} D^2} \tag{5.3}$$

where F^+ and F^- are the maximum positive and negative isolator forces, Δ^+ and Δ^- the corresponding displacements, and W_{D} the energy dissipated per cycle, which equals the area enclosed by the loop. For a friction pendulum bearing with radius of curvature R and friction coefficient μ, the effective stiffness and the period are given by Equations (5.4) and (5.5) (7,15):

$$K_{\text{eff}} = W\left(\frac{1}{R} + \frac{\mu}{D}\right) \tag{5.4}$$

$$T_{\text{eff}} = 2\pi\sqrt{\frac{W}{K_{\text{eff}} g}} \tag{5.5}$$

Equation (5.5) shows that, for a sliding bearing with a spherical surface, the period depends mainly on the radius R and not on the mass of the structure (for $\mu \to 0$, $T = 2\pi\sqrt{(R/g)}$), which explains why sliding systems are also suitable for relatively light structures, as noted in Section 3.2.2.

5-2 Effect of Period and Damping on the Seismic Demand

The reduction in acceleration that results from lengthening the period is a direct consequence of the shape of the earthquake response spectrum, as explained in Section 1-4. Figure (5.3) shows an idealized design spectrum in which the acceleration decreases with the inverse of the period for $T > 0.6$ s, whereas the displacement increases almost linearly with the period. The shaded zones indicate the period range of conventional low- and mid-rise buildings (0.2-1.0 s) and the range normally targeted by isolation systems (1.5-3.5 s), as stated in Section 3.2.1 (5). Increasing the damping reduces both the acceleration and the displacement demand. This reduction is expressed in design codes through the damping coefficient B, which divides the spectral ordinates obtained for 5% damping (13,14). Representative values are given in Table (5.2).

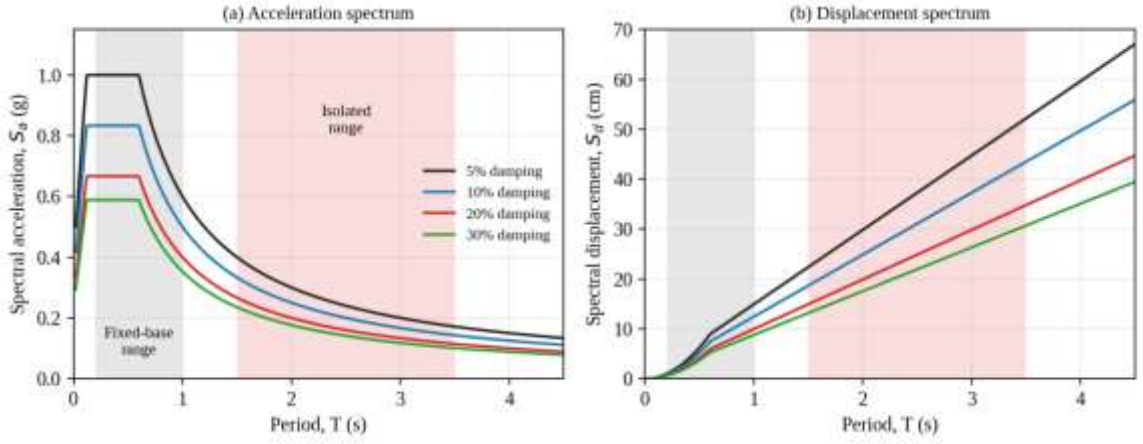


Figure (5.3) Idealized response spectra for several damping ratios (S_{DS} = 1.0 g, S_{D1} = 0.6 g, shape after reference 13; schematic, prepared by the author)

Table (5.2) Damping coefficient B as a function of the effective damping

Effective damping β_{eff} (% of critical)	Damping coefficient B	Reduction of spectral ordinates
≤ 2	0.8	Increase of 25%
5	1.0	Reference
10	1.2	17% lower
20	1.5	33% lower
30	1.7	41% lower
40	1.9	47% lower
≥ 50	2.0	50% lower

Source: damping coefficients after ASCE/SEI 7-16, Chapter 17 (13); the last column is calculated as 1 - 1/B.

The high-damping rubber bearings described in Section 2-4-1-2, with damping ratios between 8% and 20%, therefore reduce the displacement demand by roughly 10% to 33% compared with a system damped at 5% of critical, while the lead core of the LRB provides a comparable increase through hysteretic yielding (10,16).

5-3 Comparison of Isolation Devices

The characteristics of the devices discussed in Chapter 2 are compared in Table (5.3). The comparison focuses on the source of damping, the ability to re-center the structure after an earthquake, and the main limitations of each device, based on the references cited in this study (6,7,10,12).

Table (5.3) Comparison of the main types of isolation devices

Device	Main components	Source of damping	Re-centering	Main remarks
Low-damping rubber bearing (LDRB)	Thin rubber layers (5-20 mm) bonded to steel shims	Very low; supplementary dampers are needed	Yes (elastic rubber)	Flexible laterally, very stiff vertically
High-damping rubber bearing (HDRB)	Rubber compound with high damping and steel shims	Rubber compound, 8-20% of critical	Yes	Stiffer at small strains, shear modulus 0.34-1.40 MPa
Lead rubber bearing (LRB)	Rubber, steel shims and central lead plug	Yielding of the lead plug	Yes	Developed in New Zealand in 1975; combines support and damping
Friction pendulum bearing (FPS)	Spherical stainless-steel surface and Teflon-covered slider	Friction on the sliding surface	Yes (pendulum action)	Period depends on R, not on the mass
Flat sliding bearing	Two flat plates, stainless steel on low-friction material	Friction	No restoring force	Residual displacement after the earthquake
Steel springs	Coil springs	Almost none	Yes	Flexible vertically and horizontally; mainly for machinery

Source: compiled by the author from references (6), (7), (10) and (12).

5-4 Fixed-Base versus Base-Isolated Structures

Table (5.4) summarizes the main differences in behavior between a conventional fixed-base structure and a base-isolated structure, based on the principles discussed in Chapters 1 to 3 and on the design guidance in references (5) and (10).

Table (5.4) Comparison between fixed-base and base-isolated structures

Parameter	Fixed-base structure	Base-isolated structure
Fundamental period	Short, usually less than 1 s for low- and mid-rise buildings	Lengthened to about 1.5-3.5 s by the isolation layer
Seismic force on the superstructure	Full design force, with ductility needed to survive strong shaking	Reduced by a factor of about 0.30-0.80 (see Conclusion)
Location of displacement	Distributed over the stories (inter-story drift)	Concentrated in the isolators; superstructure moves almost as a rigid block
Floor accelerations	Amplified along the height	Significantly reduced
Expected damage	Structural and non-structural damage under strong earthquakes	Elastic behavior of the superstructure; non-structural elements better protected
Additional requirements	None	Rattle space (100 mm up to 1 m or more), isolation plane, inspection of bearings
Most suitable conditions	All types of structures	Heavy structures, stiff soil, no long-period ground motion

Source: compiled by the author from Chapters 1 to 3 of this study and references (5) and (10).

5-5 Influence of the Main Design Parameters

The study summarized in the abstract considers three main parameters: the height of the building, the friction coefficient of the cross-linear bearing, and the damping of the rubber isolators. The general trends of these and related parameters are summarized in Table (5.5) according to the relationships given in Section 5-1. A higher friction coefficient increases the energy dissipated per cycle and reduces the displacement, but it also increases the force transmitted to the superstructure and may reduce the re-centering capability (15). A taller superstructure has a longer fixed-base period, so the period shift obtained by the isolation system is smaller, and the overturning moment can produce tension in the isolators (5,12).

Table (5.5) General trends when a design parameter is increased

Parameter increased	Period T	Isolator displacement	Transmitted force / acceleration	Energy dissipation
Effective stiffness K_{eff}	Decreases	Decreases	Increases	Depends on the loop
Damping ratio β_{eff}	Unchanged	Decreases	Slightly decreases at the isolator; higher modes may increase	Increases
Friction coefficient μ	Slightly decreases	Decreases	Increases	Increases
Radius of curvature R (FPS)	Increases	Increases	Decreases	Unchanged
Height of the superstructure	Fixed-base period increases	Increases	Higher-mode effects increase	Unchanged
Long-period content of ground motion	Closer to resonance	Increases	Increases	Unchanged

Source: qualitative trends derived by the author from Equations (5.1) to (5.5), Table (5.2) and references (5), (10) and (15).

Design requirements for seismically isolated buildings and bridges are given in ASCE/SEI 7-16 (13) and in the AASHTO Guide Specifications for Seismic Isolation Design (14), respectively, while European requirements for the devices themselves are given in EN 15129 (19). A comparison between different design specifications is presented in reference (11).

6-1 CONCLUSION

Building seismic isolators is a technology that protects the structure from the destructive effects of an earthquake. The seismic isolators decouple the structure from the ground and provide it with damping. This decoupling allows the building to behave more flexibly which improves its response to an earthquake. The added damping allows the earthquake energy to be absorbed by the isolation systems and therefore reduces the energy transferred to the structure. Seismic isolation is physically achieved by placing the structure on isolators. The isolators are laterally flexible elements, yet they are able to carry the vertical loads of the structure. Since the isolators are more flexible than the structure, most of the lateral movements occur in the isolators. As a result the isolated structure experiences less motion and reduced forces. The concluding remarks of this study can be summarized as :

1 • The base isolation gives two important design elements to the structures: it decrease the seismic loads the superstructure by a factor of 0.30 to 0.80 and controls the distribution of these decreased lateral loads between the substructure and the foundation to then enhance the general economy and efficiency of the retrofit designs.

2 • The seismic reaction of the retrofitted structures is significantly decreased in comparison with the conventional structures, inferring that the base isolation is very successful in retrofitting the existing structures.

3 • The elastomeric and sliding systems are observed to be effective in retrofitting of the bridge, building, and other structures. The responses of seismically, isolated bridges shows benefits in the isolated direction compared to the non-isolated direction

4 • The retrofitting work can be completed without hindering or abandoning the regular activities if the structure is retrofitted using base isolation.

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