Seismic base isolation – An overview

Sajal Kanti Deb

Department of Civil Engineering, Indian Institute of Technology Guwahati, Guwahati 781 039, India

3D nonlinear analysis procedure of base isolated building is discussed here. Important issues related to design of base isolated building are presented. Shear test for obtaining force-displacement hysteresis loop of isolation bearings is outlined. Other important issues, e.g. (i) effects of soft soil on performance of base isolated building, (ii) effects of near fault motion, and (iii) soil-base isolated building interaction, as reported in the literature have also been discussed.

THE objective of seismic isolation systems is to decouple the building structure from the damaging components of the earthquake input motion, i.e. to prevent the superstructure of the building from absorbing the earthquake energy. The entire superstructure must be supported on discrete isolators whose dynamic characteristics are chosen to uncouple the ground motion. Some isolators are also designed to add substantial damping. Displacement and yielding are concentrated at the level of the isolation devices, and the superstructure behaves very much like a rigid body.

Some of the commonly used isolation systems are laminated rubber (or elastomeric) bearings and sliding isolation systems. Laminated rubber bearings are used with passive dampers for control of excessive base displacement. Laminated rubber bearings with inherent energy dissipation capacities are also developed. Lead rubber bearings and high damping rubber bearings are examples of this category of isolation system. Sliding bearings mainly utilize Teflon-stainless steel, flat or spherical, interface. Sometimes separate elements are provided for recentering of the isolated system. Performance of base isolated buildings in different parts of the world during earthquakes in the recent past established that the base isolation technology is a viable alternative to conventional earthquake-resistant design of medium-rise buildings. Three important base isolation systems[1] are shown in Figure 1.

Suitability of seismic isolation

Earthquake protection of structures using base isolation technique is generally suitable if the following conditions are fulfilled:

- The subsoil does not produce a predominance of long period ground motion.
- The structure is fairly squat with sufficiently high column load.
- The site permits horizontal displacements at the base of the order of 200 mm or more.
- Lateral loads due to wind are less than approximately 10% of the weight of the structure.

3D nonlinear dynamic analysis of base isolated buildings

In general, base isolated buildings are designed such that the superstructure remains elastic and nonlinearities are localized at the isolation level. Hence, in this paper, the superstructure is modelled by a linear elastic system and nonlinear behaviour is confined in base isolation bearings. The base and floors are assumed to be infinitely rigid in plane. The superstructure and the base are modelled using 3 degrees of freedom (DOF) per floor at the centre of mass. Each nonlinear isolation bearing is modelled using Bouc-Wen model[2]. Recently, active or semi-active devices are also used in place of passive damper for limiting excessive deformations in the isolated system. The equations of motion for superstructure and base of the isolated system are as follows:

$$\mathbf{M\ddot{u}} + \mathbf{C\dot{u}} + \mathbf{Ku} = -\mathbf{MR}(\mathbf{\ddot{u}_g} + \mathbf{\ddot{u}_b}), \tag{1}$$

$$\mathbf{R}^T\mathbf{M}[\mathbf{\ddot{u}} + \mathbf{R}(\mathbf{\ddot{u}_g} + \mathbf{\ddot{u}_b})] + \mathbf{M_b}(\mathbf{\ddot{u}_g} + \mathbf{\ddot{u}_b}) + \mathbf{C_b\dot{u}_b} + \mathbf{K_b u_b} + \mathbf{f} + \mathbf{f_c} = 0, \tag{2}$$

where $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$ = superstructure mass, damping, and stiffness matrices, respectively, in the fixed-base condition; $\mathbf{R}$ = influence matrix; $\mathbf{\ddot{u}}$, $\mathbf{\dot{u}}$, and $\mathbf{u}$ represent the floor acceleration, velocity and displacement vectors, respectively, relative to the base; $\mathbf{\ddot{u}_b}$ = vector of base acceleration relative to the ground; $\mathbf{\ddot{u}_g}$ = vector of absolute ground acceleration; $\mathbf{M_b}$ = diagonal mass matrix of the rigid base; $\mathbf{C_b}$ = resultant damping matrix of viscous isolation elements; $\mathbf{K_b}$ = resultant stiffness matrix of linear elastic isolation elements and $\mathbf{f}$ = vector containing the forces mobilized in the isolation bearings and devices, and $\mathbf{f_c}$ = control forces (null vector in case of passive control).

The forces, f, mobilized in the laminated rubber bearings can be modelled by a visco-plastic model as:

$$f_x = k_p u_x + (k_e - k_p)u^y z_x, \tag{3}$$

$$f_y = k_p u_y + (k_e - k_p)u^y z_y, \tag{4}$$

e-mail: skdeb@iitg.ernet.in

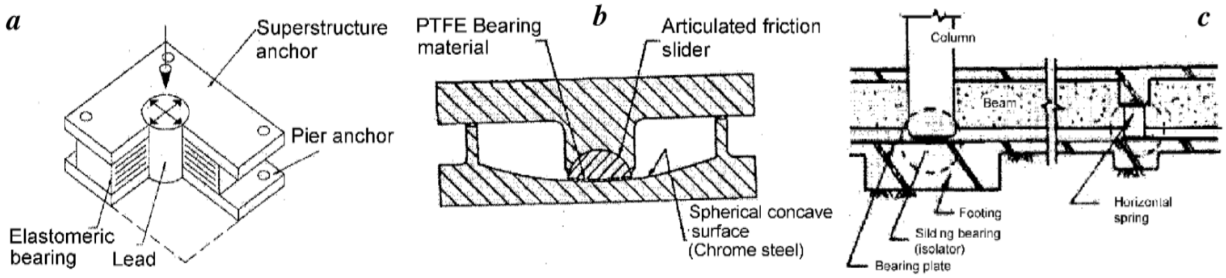

Figure 1. Three important base isolation systems. ***a***, Lead rubber bearing; ***b***, Friction pendulum system; ***c***, TASS system.

where k_e = pre-yield stiffness, k_p = post-yield stiffness, u^y is the yield displacement, z_x and z_y are dimensionless hysteretic variables defined by Park *et al.*[2].

The forces, f, mobilized in the sliding bearings can also be modelled by a visco-plastic model as:

$$f_x = k_p u_x + \mu N z_x, \tag{5}$$

$$f_y = k_p u_y + \mu N z_y, \tag{6}$$

where μ is the coefficient of friction and N is the average normal force at the bearing.

Seismic response of base isolated buildings can be obtained by solution of equations of motions (eqs (1) and (2)) by the implicit–implicit partitioned Newmark's method in predictor–corrector form for direct integration of individual coupled equations of motion in staggered fashion. Response of a three-storeyed building isolated by lead rubber bearings subjected to bi-directional Koyna (1967) accelerograms (longitudinal and transverse components along X and Y direction of the building, respectively) is shown in Figure 2 (ref. 3). It is observed that the maximum absolute roof acceleration is 1329.5 mm/s^2 as against the PGA of 0.63 g (longitudinal component).

The rigorous nonlinear analysis as described above offers an alternative to the equivalent-linear methods used by current U.S. codes for estimating isolator deformations and forces for a given spectrum. Ryan and Chopra[4] developed a procedure based on rigorous nonlinear analysis to an ensemble of ground motions representative of the spectrum. The procedure is effective because the governing equation for the system is rewritten such that its normalized deformation is insensitive to ground motion intensity, and the statistical variation of the normalized deformation to an ensemble of ground motions is minimized.

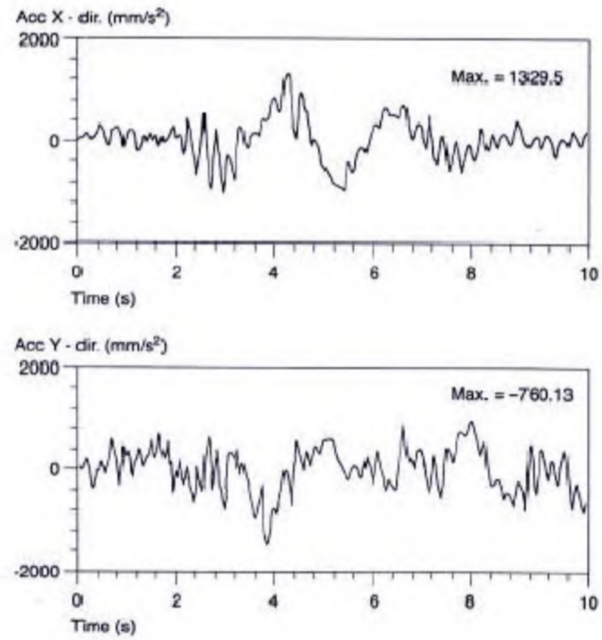

Figure 2. Absolute roof acceleration history of base isolated three storeyed building subjected to bi-directional Koyna earthquake motion.

Design parameters for seismic isolation bearing

As per IBC 2000 (ref. 5), a minimum level for design displacements and forces is to be obtained from static analysis for all seismic isolation designs. The static analysis is also useful both for preliminary design of isolation system and the structure. Dynamic analysis may be used in all cases and must be used if the requirements mentioned for adequacy of static analysis are not satisfied.

Minimum design displacements

Four distinct displacements are calculated using simple formulas used for static analysis. These values also serve as the IBC[5] permitted lower bound values for dynamic analysis results. These are:

- D_D: the design displacement, being the displacement at centre of rigidity of isolation system at design basis earthquake (DBE);
- D_M: the design displacement, being the displacement at centre of rigidity of isolation system at maximum credible earthquake (MCE);

- D_{TD}: the total design displacement, being the displacement of a bearing at a corner of the building and includes the component of the torsional displacement in the direction of D_D;
- D_{TM}: same as D_{TD} but calculated for MCE.

D_D and D_M are given as:

$$D_D = \frac{(g/4\pi^2)S_{D1}T_D}{\beta_D}, \quad (7)$$

$$D_M = \frac{(g/4\pi^2)S_{M1}T_M}{\beta_M}, \quad (8)$$

where g is the acceleration due to gravity, S_{D1} and S_{M1} are spectral coefficients, T_D and T_M are isolated periods, and β_D and β_M are damping coefficients corresponding to the DBE and MCE level responses, respectively.

Effective isolated system periods

The effective isolated periods T_D and T_M corresponding to the DBE and MCE level response are:

$$T_D = 2\pi\sqrt{\frac{W}{K_{D,\min}g}}, \quad (9)$$

$$T_M = 2\pi\sqrt{\frac{W}{K_{M,\min}g}}, \quad (10)$$

where W = the weight of the building; g = acceleration due to gravity; $K_{D,\min}$ = minimum effective horizontal stiffness of the isolation system at the design displacement (DBE). $K_{M,\min}$ = minimum effective horizontal stiffness of the isolation system at the maximum displacement (MCE).

The values of $K_{D,\min}$ and $K_{M,\min}$ are not known during preliminary design phase and hence the design process will begin with an assumed value which is obtained from previous tests on similar components. After moulding of prototype bearing, the actual values of $K_{D,\min}$, $K_{D,\max}$, $K_{M,\min}$ and $K_{M,\max}$ will be obtained from the results of shear test on bearings. $K_{D,\max}$ and $K_{M,\max}$ are maximum effective stiffness at displacement corresponding to DBE and MCE, respectively.

The total design displacements, D_{TD} and D_{TM} are given as:

$$D_{TD} = D_D\left(1 + y\frac{12e}{b^2 + d^2}\right), \quad (11)$$

$$D_{TM} = D_M\left(1 + y\frac{12e}{b^2 + d^2}\right), \quad (12)$$

where b and d are plan dimensions at the isolation plane, e is the actual eccentricity plus 5% accidental eccentricity, and y is the distance to a corner perpendicular to the direction of seismic loading.

Design forces

The superstructure and elements below the isolation interface are designed for forces based on DBE design displacement, D_D. The isolation system, the foundation and structural elements below the isolation system must be designated to withstand the following minimum lateral seismic force:

$$V_b = K_{D,\max}D_D. \quad (13)$$

If other displacements rather than D_D generate larger forces, then those forces should be used in design rather than the force obtained from eq. (13).

The structure above the isolation plane should withstand a minimum shear force, V_s, as if it is fixed base where:

$$V_s = \frac{K_{D,\max}D_D}{R_I}. \quad (14)$$

In IBC 2000, R_I is defined as

$$1.0 \le R_I = 3/8\ R \le 2.0, \quad (15)$$

where R is reduction factor defined in the code for superstructure.

Testing requirements for isolators

The IBC-2000 (ref. 5) code requires that at least two full-sized specimens of each type of isolator be tested. The tests required are a specified sequence of horizontal cycles under $DL + 0.5LL$ from small horizontal displacements up to D_{TM}. In addition, tests are also carried out for the maximum vertical load $1.2DL + 0.5LL + E_{\max}$ and for the minimum load $0.8DL - E_{\min}$ where $E_{\max}$ and $E_{\min}$ are the maximum downward and upward load on the isolator that can be generated by an earthquake.

Test set-up for shear test of laminated rubber bearing

Aiken *et al.*[6] carried out extensive testing of high damping laminated rubber bearings (LRB) using a typical set-up for shear test shown in Figure 3. On the basis of the test results a number of comparisons have been made for bearings with different characteristics. The influence of axial load and shear strain on bearing characteristics, e.g. shear stiffness, vertical stiffness, and damping behaviour have been investigated. Figure 4 shows a typical force-displacement hysteresis loop of high damping LRB obtained during shear test. The shear tests demonstrated that the LRBs possess stable stiffness and damping properties.

Base isolation on soft soil

Although the concept of base isolation is gaining widespread acceptance in different parts of the world, a question is being raised over performance of base isolated building located at soft soil sites as to the effect of a low-site natural frequency on isolated structures. To address these concerns, Kelly[7] carried out an experimental study on shake table at EERC, University of California at Berkeley. Two different isolation systems were used in the shake table tests. One isolation system was designed to provide the model with a natural period that corresponds to the period of a proposed nuclear facility. The second system made use of newly developed high damping rubber with low shear modulus which provides a frequency of about 25% lower than that given by the first system. This allowed the assessment of (i) the benefits of lengthening the period of isolation system where the site is particularly soft and (ii) the practicality of long-period isolation systems based on elastomeric components. The test series has shown that the base isolation systems can be used at soft-soil sites under circumstances where load on the isolation system and, consequently, sizes of the isolation systems are sufficiently large to accommodate the resulting large displacement.

Base isolation for near-fault motions

In the recent past, a number of accelerograms from near-source sites have been recorded. Seismic response of base-isolated structures subjected to such accelerograms raised the issue of suitability of isolation system in near-fault locations. There are two aspects of near-fault ground motion that influences base isolated structures[8]. First, the ground motion normal to the fault trace is richer in long-period spectral components than that parallel to the fault. The fault normal and fault parallel motions are more or less uncorrelated, and the fault parallel motion often exhibits higher spectral acceleration components at short periods than the fault normal motion. The resultant maximum bearing displacement is mainly due to the normal component of the near-fault motions. The contribution from the parallel component in the resultant displacement may be ignored.

The second aspect of near-fault ground motion that strongly impacts seismic isolation systems is the presence of long-duration pulses. The ground motions may have one or more displacement pulses, with peak velocities of the order of 0.5 m/s and durations in the range of 1–3 s. These pulses will have a large impact on an isolation system with a period in this range and can lead to a large isolator displacement. The large displacements can be accommodated by using large isolators. Figure 5 illustrates how a system of transfer trusses in the lower portion of a frame is used to bring load from 24 columns into only 8 nos. of bearings. This concept has been used in large buildings in Japan to take care of large displacement demand on the isolation system.

A comparative study on performance of various isolation systems in near-fault locations has been carried out by Jangid and Kelly[8]. It is observed that EDF-type isolation systems may be optimum choice for design of isolated structures in near-fault locations.

Base isolated buildings with SSI

The influence of soil–structure interaction (SSI) and possible effects of building and foundation rocking are examined by investigating the modal properties of the isolated

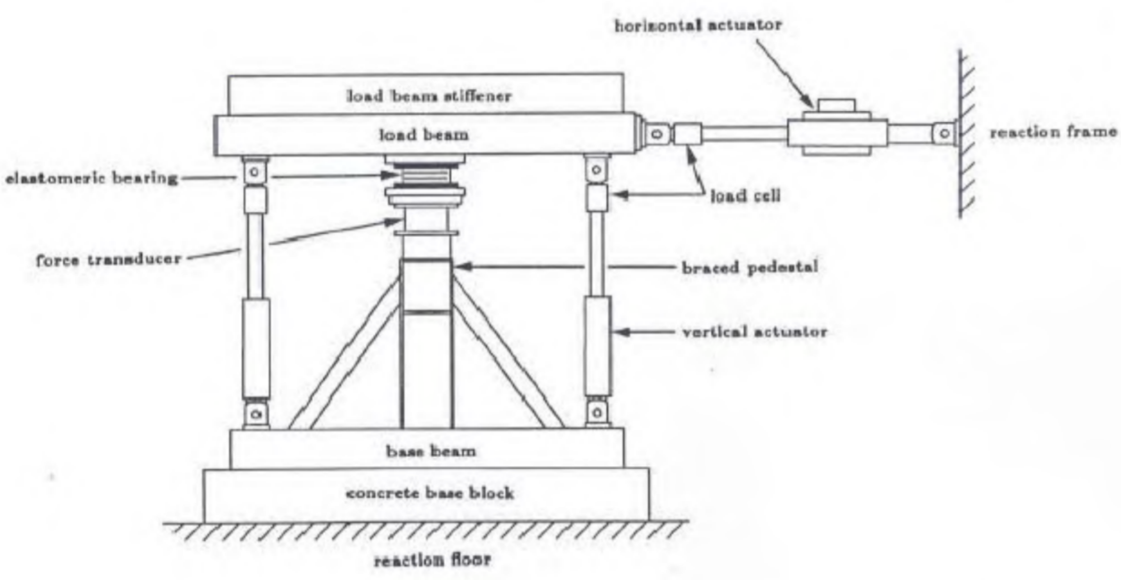

Figure 3. Typical set up for shear test of laminated rubber bearing.

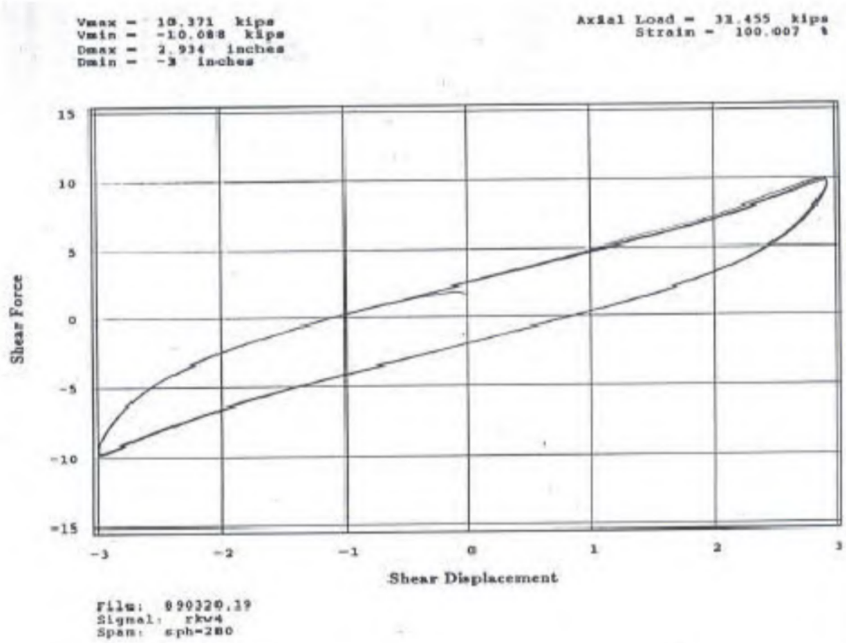

Figure 4. A typical force-displacement hysteresis loop of laminated rubber bearing.

Figure 5. Transfer trusses in lower stories of a base isolated building.

system[9]. The effect of soil–structure interaction on modal properties and seismic forces is small when the isolators are much more flexible, than the soil; when the flexibilities of the isolators and soil are comparable, the soil may contribute to the building behaviour. It is also observed that cross-interaction between spread footings is not a significant factor for response in the fundamental mode and can have a marked effect on higher modes.

Concluding remarks

In this era of technological revolution, the world of seismic engineering is in need of creative thinking and advanced technology beyond conventional solutions. Seismic isolation is a suitable technology for protection of a variety of buildings that have the requisite dynamic characteristics. Isolation technology has matured in recent years to highly dependable and reliable level. Academic research on the subject is well advanced, and its practical application is becoming widespread throughout the world.

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