3D-BASIS: Computer Program Series for Nonlinear Dynamic Analysis of Three-Dimensional Base Isolated Structures

by Andrei Reinhorn, Michael Constantinou and Satish Nagarajaiah

Abstract

3D-BASIS is a series of special purpose computer programs designed to analyze structures with nonlinear base isolation devices subjected to seismic motion. The series evolved from analysis of simplified structural models represented by condensed formulations ("stick representation"), to more elaborated structural models of components such as building columns, beams, walls, and water containers, combined in complex structural systems.

The program was developed to enable analysis of various isolation devices such as elastomeric bearings with low and high damping characteristics, sliding bearings, linear springs with complementary damping devices such as viscous fluids, viscoelastic, friction, and others, under realistic three-dimensional seismic motion.

The program series, which includes 3D-BASIS, 3D-BASIS-M, 3D-BASIS-ME and 3D-BASIS-TABS, was distributed to the engineering and to the academic communities. These programs enabled analysis and design of complex structures and advanced the practical application of base isolation in seismic areas (both in the U.S. and overseas).

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Objectives and Approach

The objective of this research task was to develop a computer program to analyze base isolated structures. There was a need to develop a modeling tool to integrate base isolation devices into structural systems and to predict how the presence of these systems affect the structure. A family of computer programs, 3D-BASIS, was developed to analyze base isolation systems while attached to a variety of structures and to model the interaction between the isolation system and the structure.

The research effort was directed toward modeling nonlinear isolation components, and calibrating these models by experimental data and analytical formulations. Groups or clusters of components were modeled, and the behavior of the resulting structural assemblages and isolators were validated through shake table testing. The performance of the program was also compared to other commercially available programs, which can analyze some of the configurations of isolation systems, but in less efficient ways.

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Introduction

The modeling of individual seismic isolation bearings advanced quickly in the last two decades (Buckle, 1993). Exploratory testing and analytical modeling of elastomeric bearings enabled the use of such bearings in simple structures. More devices were subsequently suggested, tested and modeled. The need to integrate such devices in building structures, bridges, and other special structures, and to predict the behavior of such structures in the presence of isolation systems motivated the development of a series of specialized computer programs, 3D-BASIS. This series was developed to analyze groups of isolation bearings, and damping devices modeled individually by nonlinear mathematical rules, attached to structural models, which in turn are affected by the seismic isolation system.

As the structure also exerts forces on the isolation system, the interaction between the isolation system and structure is essential in the analysis or the design. This interaction cannot be captured by analyzing the components alone. The program series 3D-BASIS allows for versatile modeling of isolators and superstructures using simple models and general solutions that permit analysis of very complex systems. Moreover, the flexible design of the program allows more isolation components to be easily added without restructuring the program or the solutions.

The research effort was directed toward modeling nonlinear isolation components (such as elastomeric bearings, high or low damping rubber bearings, sliding bearings, linear and nonlinear viscoelastic devices) calibrated by experimental data and by the latest analytical formulations. Moreover, groups or clusters of components were modeled analytically while calibrating them by experiments [such as triaxial interaction in isolation bearings, (Mokha et al.)]. Furthermore, the resulting assemblages of structures and isolators were validated by shaking table testing to emphasize the accuracy and the sensitivity of the program (Mokha, et al., Constantinou, et al., Nagarajaiah et al., Hisano et al.). The performance of this program was also compared to the performance of other commercially available programs, which can analyze some of the configurations of isolation systems, but in a less efficient way. The numerical schemes selected for the 3D-BASIS series, which employ static and dynamic condensations before a step-by-step time analysis, complemented by the pseudo-force technique, produce extremely fast and accurate solutions suitable for verification of design assumptions.

The resulting product is a versatile tool for analysis and design of complex structures with modern isolation. As such, it provides support in the research and development of individual isolation devices that can be immediately verified for practicality in an integrated system. Moreover, the resulting program can and did provide support for the design of isolated structures such as large hospitals, emergency response structures, hazardous materials storage structure, and historic buildings, to name a few. The program has been and is used in verification and development of new standards for design of base isolated structures.

Overview of 3D-BASIS Series

The series 3D-BASIS (i.e., 3D-BASIS; Nagarajaiah, Reinhorn, and Constantinou, 1989, 1991a; 3D-BASIS-M; Tsopelas, Nagarajaiah, Constantinou and Reinhorn, 1991; 3D-BASIS-ME; Tsopelas, Constantinou and Reinhorn (1994); 3D-BASIS-TABS; Nagarajaiah, Li, Reinhorn and Constantinou, 1993, 1994) was developed for the public domain for the analysis of base isolated structures. The basic features of the program are:

- Detailed or reduced/condensed modeling of the superstructure assumed elastic at all times.

- Detailed modeling of the isolation system with spatial distribution of isolation elements.

- Library of isolating elements which include elastomeric and sliding bearings with bi-directional interaction effects and rate loading influences.

- Library of supplementary damping or restraint devices and specialized bearings with either linear or nonlinear characteristics.

- Time domain solution algorithm for very stiff differential equations with adjustable time step.

- Triaxial excitation including vertical effects.

- Recovery of element stress time histories in superstructure and isolation system.

Superstructure Modeling: The superstructure is assumed to remain elastic at all times. Coupled lateral-torsional response is accounted for by maintaining three degrees-of-freedom per floor, that is two translational and one rotational degrees-of-freedom. Three options exists in modeling the superstructure:

1. Full modeling of structural elements in a superstructure assembly which assumes in-plane rigid floors with three degrees-of-freedom per floor. The stiffness formulation and the dynamic characteristics are obtained through a preprocessing package adapted from ETABS (Wilson et al., 1975) and integrated in 3D-BASIS-TABS.

2. Shear type representation in which the stiffness matrix of the superstructure is internally constructed by the program. It is assumed that the centers of mass of all floors lie on a common vertical axis, floors are rigid and walls and columns are inextensible. Single (3D-BASIS) and multiple (3D-BASIS-M and 3D-BASIS-ME) shear structures assemblies (vertical axes) can be attached to one isolation system via a rigid base matt.

3. Dynamically condensed three-dimensional representation in which the dynamic characteristics of the superstructure are determined by

other computer programs (e.g., ETABS, Wilson et al. 1975) and imported to program 3D-BASIS. In this way, the extensibility of the vertical elements, arbitrary location of centers of mass and floor flexibility may be implicitly accounted for. Still however, the condensed model for dynamic analysis maintains three degrees-of-freedom per floor or substructure in case of multiple towers.

In all options, the data needed for the step-by-step dynamic analysis are the mass and the moment of inertia of each floor, frequencies, mode shapes and associated damping ratios for a number of modes. A minimum of three modes of vibration of the superstructure need to be considered.

Isolation System Modeling: The isolation system is modeled with spatial distribution and explicit or implicit nonlinear force-displacement characteristics of individual isolation devices. The isolation devices are considered rigid in the vertical direction and individual devices are assumed to have negligible resistance to torsion. Program 3D-BASIS has the following elements for modeling the behavior of an isolation system:

1. Linear Elastic elements.
2. Linear and Nonlinear Viscous elements.
3. Hysteretic elements for elastomeric bearings and steel dampers with and without stiffening characteristics.
4. Hysteretic elements for sliding bearings.

In addition, the above elements were clustered in combined elements to represent more complex isolation bearings (sliding friction pendulum bearing, high damping rubber bearing with stiffening characteristics) and other isolators with more complex behavior (i.e., variable pressure sliding, overturning effects, etc.).

Uniaxial Linear Elastic Element/Linear Viscous Element: The linear elastic element can be used to approximately simulate the behavior of elastomeric bearings along with the linear viscous element. All linear elastic devices and linear viscous devices of the isolation system specified are combined, internally by the program in global elements, having the combined properties of all the devices, at the center of mass of the base.

Uniaxial Nonlinear Viscous Element: The nonlinear viscous element represents fluid behavior in specially designed orifices to control the force output as a nonlinear function of the relative velocity, based on experimental and analytical modeling. This element can be used to simulate supplemental damping at the base (viscous damping devices) required to moderate the isolation's lateral sways.

Model for Biaxial Isolation Elements: The model for biaxial interaction presented herein accounts for the direction and magnitude of the resultant hysteretic force; it is based on the following set of equations proposed by Park, Wen, and Ang (1986):

$$\begin{Bmatrix} \dot{Z}_x Y \\ \dot{Z}_y Y \end{Bmatrix} = \begin{Bmatrix} A\dot{U}_x \\ A\dot{U}_y \end{Bmatrix} - \begin{bmatrix} Z_x^2\left(\gamma\, Sign\left(\dot{U}_x Z_x\right)+B\right) & Z_x Z_y\left(\gamma\, Sign\left(\dot{U}_y Z_y\right)+B\right) \\ Z_x Z_y\left(\gamma\, Sign\left(\dot{U}_y Z_y\right)+B\right) & Z_x^2\left(\gamma\, Sign\left(\dot{U}_x Z_x\right)+B\right) \end{bmatrix} \begin{Bmatrix} \dot{U}_x \\ \dot{U}_y \end{Bmatrix} \tag{1}$$

in which $\dot{U}_x$ and $\dot{U}_y$ are velocities of the *X* and *Y* directions, Z_x and Z_y are hysteretic dimensionless quantities, *Y* is the yielded displacement, *A*, γ and β are dimensionless quantities that control the shape of the hysteresis loop. The values of $A = 1$, $\gamma = 0.9$ and $\beta = 0.1$ are used in this report. Z_x and Z_y are bounded by values ±1 and account for the direction and biaxial interaction of hysteretic forces.

Biaxial Model for Sliding Bearings: For a sliding bearing, the mobilized forces are described by the equations (Constantinou et al., 1990):

$$F_x = \mu_s W Z_x \quad ; \quad F_y = \mu_s W Z_y \tag{2}$$

in which *W* is the vertical load carried by the bearing and μ_s is the coefficient of sliding friction which depends on the value of bearing pressure, angle θ and the instantaneous velocity of sliding Z_x and Z_y which are bounded by the values ±1, account for the conditions of separation and reattachment (instead of a signum function) and also account for the direction and biaxial interaction of frictional forces.

The coefficient of sliding friction is modeled by the following equation (Constantinou et al., 1990):

$$\mu_x = f_{max} - \left(f_{max} - f_{min}\right) \bullet exp\left(-\alpha\left|\dot{U}\right|\right) \tag{3}$$

in which f_{max} and f_{min} are the maximum and the minimum (at $\dot{U}$=o) values of the coefficient of friction, respectively.

Biaxial Model for Elastomeric Bearings and Steel Dampers: For an elastomeric bearing, the mobilized forces are described by the equations:

$$\begin{aligned} F_x &= \alpha \frac{F^y}{Y} U_x + (1-\alpha) F^y Z_x \; ; \\ F_y &= \alpha \frac{F^y}{Y} U_y + (1-\alpha) F^y Z_y \end{aligned} \tag{4}$$

in which α is the post-yielding and pre-yielding stiffness ratio, F^y is the yield force, and Y is the yield displacement, Z_x and Z_y account for the direction and biaxial interaction of hysteretic forces.

Special Elements and Procedures: A combination between a linear restoring force and a friction sliding device were combined to simulate a special bearing dependent on the variation of vertical loads, i.e., friction pendulum bearing (see example in the following section).

Special modifications to elements and structural modeling were performed to include the influence of overturning moment and of the vertical ground accelerations.

A nonlinear stiffening hysteretic model was formulated to simulate high damping rubber bearings that experience such behavior.

Global System Assembly

The superstructure is modeled as an elastic frame-wall structure with three degrees-of-freedom per floor. The three degrees-of-freedom are attached to the center of mass of each floor and base. The floors and the base are assumed to be infinitely rigid inplane. The isolation system may consist of elastomeric and/or sliding isolation bearings, linear springs, and viscous elements.

The equations of motion for the elastic superstructure are expressed in the following form:

$$\begin{aligned} & M_{nxn}\ddot{u}_{nx1} + C_{nxn}\dot{u}_{nx1} + K_{nxn}u_{nx1} = \\ & -M_{nxn}R_{nx3}\left\{\ddot{u}_g + \ddot{u}_b\right\}_{3x1} \end{aligned} \tag{5}$$

in which η is three times the number of floors, M is the diagonal superstructure mass matrix, C is the superstructure damping matrix, K is the superstructure stiffness matrix and R is the matrix of earthquake influence coefficients, i.e. the matrix of displacements and rotation at the center of mass of the floors resulting from a unit translation in the X and Y directions and unit rotation at the center of mass of the base (with respect to global structure reference axis). Furthermore, the equations of motion for the base are as follows:

$$\begin{aligned} & R^T_{3xn}\, M_{nxn}\left\{\left\{\ddot{u}\right\} + R\left\{\ddot{u}_b + \ddot{u}g\right\}\right\}_{x1} \\ & + M_{b3x3}\left\{\ddot{u}_b + \ddot{u}g\right\}_{3x1} + C_{b3x3}\left\{\dot{u}_b\right\} \\ & + K_{b3x3}\left\{u_b\right\}_{3x1} + \left\{f\right\}_{3x1} = 0 \end{aligned} \tag{6}$$

In which M_b is the diagonal mass matrix of the rigid base, C_b is the resultant damping matrix of viscous isolation elements, K_b is the resultant stiffness matrix of elastic isolation elements and f is the vector containing the forces mobilized in the nonlinear elements of the isolation system such as the presented elements for sliding or elastomeric bearings.

Employing a dynamic condensation to the elastic superstructure's degrees of freedom by means of model reduction, the number of the equations to be solved is reduced to the number of retained modes and the degrees of freedom of the foundation.

$$u_n = \Phi_{nxm} u^*_{mx1} \tag{7}$$

in which Φ is the modal matrix of the fixed base superstructure normalized with respect to the mass matrix, and u^* is the modal displacement vector relative to the base and m is the number of eigenvectors retained in the analysis; combining Eqs. (5) to (7), the following equation is derived: in which ξ_I = the modal damping ratio, and ω_i = the natural frequency of the fixed based structure in the mode i. In Eq. (8) matrices $[2\xi_I\omega_i]$ and $\left[\omega_i^2\right]$ are diagonal. Eq. (8) can be written as follows at times t and $t + \Delta t$:

$$\begin{pmatrix} [I] & \left[\Phi^T MR\right] \\ \left[R^T M\Phi\right] & \left[R^T MR + M_b\right] \end{pmatrix}_{(m+3)x(m+3)} \begin{Bmatrix} \ddot{u}^* \\ \ddot{u}_b \end{Bmatrix}_{(m+3)x1} + \begin{pmatrix} [2\xi_i\omega_i] & 0 \\ 0 & [C_b] \end{pmatrix}_{(m+3)x(m+3)} \begin{Bmatrix} \dot{u}^* \\ \dot{u}_b \end{Bmatrix}_{(m+3)x1}$$

$$+ \begin{pmatrix} \left[\omega_1^2\right] & 0 \\ 0 & [K_b] \end{pmatrix}_{(m+3)x(m+3)} \begin{Bmatrix} u^* \\ u_b \end{Bmatrix}_{(m+3)x1} + \begin{Bmatrix} 0 \\ f \end{Bmatrix}_{(m+3)x1} = - \begin{bmatrix} \Phi^T MR \\ R^T MR + M_b \end{bmatrix}_{(m+3)x3} \ddot{u}_{g3x1} \tag{8}$$

$$\begin{aligned} &\tilde{M}_{\ddot{u}_i} + \tilde{C}_{\dot{u}_t} + \tilde{K}_{\tilde{u}_t} + f_t = \tilde{P}_t \quad ; \\ &\tilde{M}_{\ddot{u}_{t+\Delta t}} + \tilde{C}_{\dot{u}_{t+\Delta t}} + \tilde{K}_{\tilde{u}_{t+\Delta t}} + f_{t+\Delta t} = \tilde{P}_{t+\Delta t} \end{aligned} \tag{9}$$

Written in incremental form

$$\begin{aligned} &\tilde{M}\Delta_{\ddot{u}_{t+\Delta t}} + \tilde{C}\Delta_{\dot{u}_{t+\Delta t}} + \tilde{K}\Delta_{\tilde{u}_{t+\Delta t}} + \Delta f_{t+\Delta t} \\ &= \tilde{P}_{t+\Delta t} - \tilde{M}_{\ddot{u}_t} - \tilde{C}_{\dot{u}_t} - \tilde{K}_{\tilde{u}_t} - f_t \end{aligned} \tag{10}$$

in which $\tilde{M}$, $\tilde{C}$, $\tilde{K}$ and $\tilde{P}$ represent the reduced mass, damping, stiffness and load matrices [compare Eq. (9) with Eq.(8)]. Furthermore, the state of motion of modal superstructure and base is represented by vectors $\ddot{\tilde{u}}_t$, $\dot{\tilde{u}}_t$ and $\tilde{u}_t$ [see Eq. (8)].

Solution Procedure

The solution procedure includes assembly of stiffness matrices from the structural data, search from dynamic properties via an eigenvalue analysis, formulation of loading conditions, solution of equations of motion, and step-by-step and back substitution to recover the history of members/ element forces. The following is a brief description of these procedures.

Superstructure Stiffness Assembly: 3D-BASIS is designed to include three options for modeling the superstructure, option 1 for 3D-shear building in which case story stiffnesses are to be input, option 2 for full 3D-building in which case member properties for beam, column, etc. are to be input, for detailed member by member representation of the superstructure, option 3 for full 3D-building in which case eigenvalues/eigenvectors are to be input. If option 1 or 3 is used, member forces are not output as no data for representing individual members is available.

(a) In option 1, the superstructure of the three-dimensional shear building is represented by a global stiffness matrix assembled using story stiffnesses specified by the user. It is assumed that the centers of mass of all the floors lie on the common vertical axis, floors and beams are rigid, and walls and columns are inextensible.

(b) In option 2, the procedure for assembly of the stiffness matrix of the frame substructure from ETABS (Wilson et al., 1975) is adopted. The members of the superstructure are modeled using the linear elastic element for beam, columns, shear walls, and bracing members. Each joint in the structure is modeled with six degrees-of-freedom. Within each frame joint, three degrees of freedom (the two translations and one rotation in the floor plane) are transformed, using the rigid floor diaphragm, to the frame degrees-of-freedom at the floor level. The remaining three frame joint degrees of freedom are eliminated by static condensation. After condensation, each frame substructure stiffness is transformed and added to the global structural stiffness. The global degrees-of-freedom are three degrees of freedom per floor. The global stiffness matrix of the superstructure in the fixed base condition is used for eigenvalue analysis.

(c) In option 3, the superstructure of the three-dimensional building is represented by a global stiffness matrix, assembled using dynamic characteristics such as frequencies and mode shapes specified by the user. Implicit in this approach is that the axial deformation of columns, bending and shear deformation of column and beam members, and arbitrary location of the center of mass, are accounted for by the condensed dynamic characteristics. However, the model for dynamic analysis still maintains only three degrees-of-freedom per floor.

Eigenvalue Analysis: An analysis is performed to determine the eigenvalues and eigenvectors, i.e., frequencies and mode shapes in the fixed base condition using the condensed global stiffness matrix. The frequencies and mode shapes are used in the global system assembly. The frequencies and mode shapes obtained correspond to the condensed three degrees-of-freedom per floor.

Loading Conditions: Vertical static loading conditions for representing dead loads and earthquake load conditions representing seismic excitation can be specified. The vertical loading conditions can include up to three independent vertical load distributions (I,II,III), and these distributions are combined to form load cases for the complete building. For earthquake loading conditions, bi-directional lateral ground motions and a vertical ground motion can be specified.

Solution for Global System Response: The incremental nonlinear force vector $\Delta f_{t+\Delta t}$ in Eq. (10) is unknown. This vector is brought on to the right hand side of Eq. (10) and treated as *pseudo-force vector*. The two step solution algorithm developed is as follows: (1) the solution of equations of motion using unconditionally stable Newmark's constant-average-method of the nonlinear isolation elements using unconditionally stable semi-implicit Runge-Kutta method suitable for solution of stiff differential equations. Furthermore, an iterative procedure consisting of corrective pseudo-forces is employed within each time step until equilibrium is achieved. Detailed explanation of the solution algorithm can be found in Nagarajaiah et al. (1991a) and is shown in table 1.

Backsubstitution/Output Data: The time history of member forces are computed by backsubstitution, after the nonlinear time history analysis is completed. The peak member forces and time histories are output to facilitate the design of members. The backsubstitution procedure from ETABS is adopted.

Examples of Program Verifications

The program was verified by using several practical applications which were analyzed during the current program and compared to commercially available, less specific programs. A detailed presentation of various verifications and modeling techniques were presented in detail in

A. Initial Conditions:

1. Form stiffness matrix $\bar{K}$, mass matrix $\bar{M}$, and damping matrix $\bar{C}$. Initialize $\bar{u}_0$, $\dot{\bar{u}}_0$ and $\ddot{\bar{u}}_0$.
2. Select time step Δt, set parameters $\delta = 0.25$ and $\theta = 0.5$, and calculate the integration constants:

$$\alpha_1 = \frac{1}{\delta(\Delta t)^2};\quad \alpha_2 = \frac{1}{\delta \Delta t};\quad \alpha_3 = \frac{1}{2\delta};\quad \alpha_4 = \frac{\theta}{\delta \Delta t};\quad \alpha_5 = \frac{\theta}{\delta};\quad \alpha_6 = \Delta t\left(\frac{\theta}{2\delta} - 1\right)$$

3. Form the effective stiffness matrix $K^* = \alpha_1 \bar{M} + \alpha_4 \bar{C} + \bar{K}$
4. Triangularize K^* using Gaussian elimination (only if the time step is different from the previous step).

B. Iteration at each time step:

1. Assume the pseudo-force $\Delta f^{i}_{t+\Delta t} = 0$ in iteration $i = 1$.
2. Calculate the effective load vector at time $t + \Delta t$:

$$P^*_{t+\Delta t} = \Delta \bar{P}_{t+\Delta t} - \Delta f^{i}_{t+\Delta t} + \bar{M}(\alpha_2 \dot{\bar{u}}_t + \alpha_3 \ddot{\bar{u}}_t) + \bar{C}(\alpha_5 \dot{\bar{u}}_t + \alpha_6 \ddot{\bar{u}}_t)$$

$$\Delta \bar{P}_{t+\Delta t} = \bar{P}_{t+\Delta t} - (\bar{M}\ddot{\bar{u}}_t + \bar{C}\dot{\bar{u}}_t + \bar{K}\bar{u}_t + f_t)$$

3. Solve for displacements at time $t + \Delta t$: $K^* \Delta u^{i}_{t+\Delta t} = P^*_{t+\Delta t}$
4. Update the state of motion at time $t + \Delta t$:

$$\ddot{\bar{u}}_{t+\Delta t} = \ddot{\bar{u}}_t + \alpha_1 \Delta \bar{u}^{i}_{t+\Delta t} - \alpha_2 \dot{\bar{u}}_t - \alpha_3 \ddot{\bar{u}}_t;\quad \dot{\bar{u}}_{t+\Delta t} = \dot{\bar{u}}_t + \alpha_4 \Delta \bar{u}^{i}_{t+\Delta t} - \alpha_5 \dot{\bar{u}}_t - \alpha_6 \ddot{\bar{u}}_t;\quad \bar{u}_{t+\Delta t} = \bar{u}_t + \Delta \bar{u}^{i}_{t+\Delta t}$$

5. Compute the state of motion at each bearing and solve for the nonlinear force at each bearing using semi-implicit Runge-Kutta method.
6. Compute the resultant nonlinear force vector at the center of mass of the base $\Delta f^{i+1}_{t+\Delta t}$.
7. Compute

$$Error = \frac{\left|\Delta f^{i+1}_{t+\Delta t} - \Delta f^{i}_{t+\Delta t}\right|}{Ref.\mathrm{Max}.Moment}$$

Where $|.|$ is the euclidean norm

8. If Error $\geq$ tolerance, further iteration is needed, iterate starting form step B-1 and use $\Delta f^{i+1}_{t+\Delta t}$ as the pseudo-force and the state of motion at time t, $\bar{u}_t$, $\dot{\bar{u}}_t$ and $\ddot{\bar{u}}_t$.
9. If Error $\leq$ tolerance, no further iteration is needed, update the nonlinear force vector: $f_{t+\Delta t} = f_t + \Delta f^{i+1}_{t+\Delta t}$ reset time step if necessary, go to step B-1 if the time step is not reset or A-2 if the time step is reset.

Table 1
Solution Algorithm

previous NCEER reports (Nagarajaiah et al., 1989; Tsopelas et al., 1991; Mokha et al., 1989; and most recently by Nagarajaiah et al., 1993 and Tsopelas et al., 1994). Two examples were selected to be presented here: (i) a six-story building structure isolated with lead rubber bearings; (ii) a large liquid natural gas storage tank containing hazardous liquid and supported by a seismic isolation made of "friction pendulum system", a dry friction sliding support.

Six-story reinforced concrete structure with lead-rubber bearing isolation system

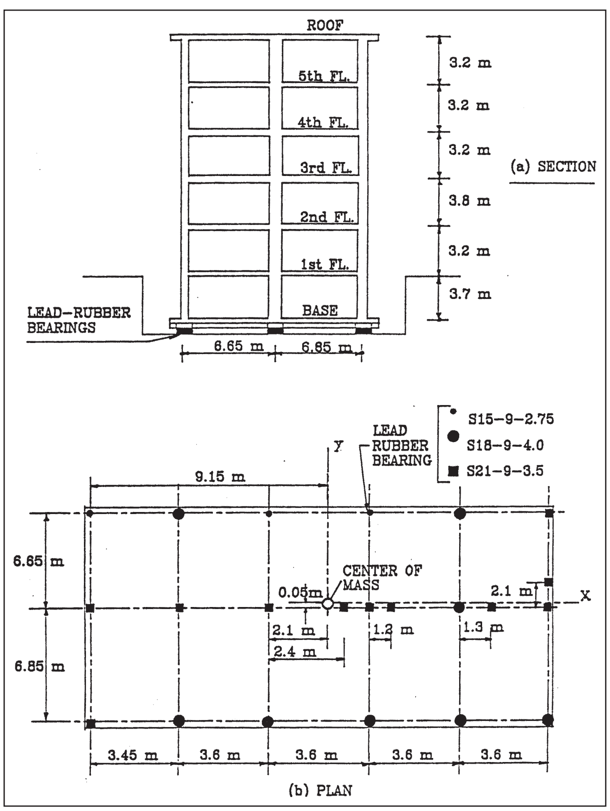
The analysis of a six-story reinforced concrete base isolated structure with a lead rubber bearing isolation system is considered. A view of the building is provided in figure 1. The plan and section of the building are shown in figure 2. The reinforced concrete superstructure is designed to resist lateral loads equivalent to a seismic base shear coefficient of *0.15g* using shear walls. Damping of 5% of a critical is used for the superstructure in all the modes. 3D-BASIS-TABS is used to model the superstructure (i) using option 2, member-by-member modeling; and (ii) using option 3, with eigenvalues and eigenvectors.

The lead-rubber bearing isolation system design is based on the procedure developed by Dynamic Isolation Systems (1993), and consists of 22 lead-rubber bearings (see figure 2b). A site specific response spectrum is used in the design of the structure/isolation system. The average isolation yield level Q_a is set to *0.045W,* where *W*

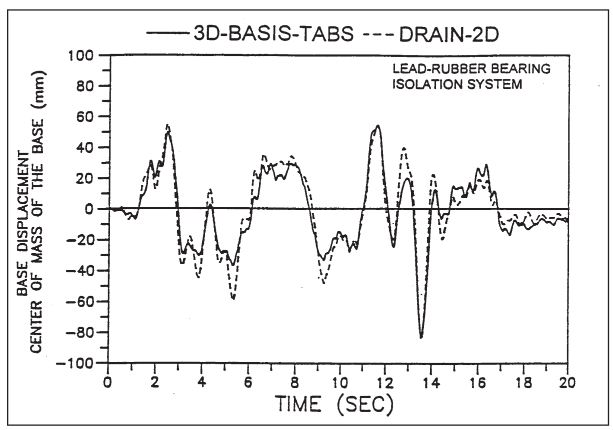
■ **Figure 1**
View of U.S. Court of Appeals Building in San Francisco, California, isolated with friction pendulum bearings

is the total weight of the structure (= 25143 *kN*). The rigid body isolation period T_b, is 1.65 seconds. The dynamic response is computed for an artificial accelerogram of 20 seconds duration. The artificial accelerogram is realized from the site specific response spectrum. For more details about the isolation system parameters and the artificial accelerogram, refer to Nagarajaiah et al. (1991).

To verify the response, the structural stiffness properties are condensed to six degrees of freedom (one per floor in the *Y* direction) and used for a two-dimensional analysis using DRAIN-2D (Kannan and Powell, 1974). The properties of the isolation system are lumped with F^y = 1328 *kN*, Y = 0.00525 meters, α = 0.148 and Q_a = 0.045W, in a single isolation element, resulting in T_b = 1.65 seconds. The same artificial accelerogram used in 3D-BASIS-TABS analysis is used as the excitation. The base displacement response (*Y* direction) is shown in figure 3. The comparisons between the results of 3D-BASIS-TABS and DRAIN-2D, shown in figure 3, indicate good agreement. Also, the results of 3D-BASIS-TABS and the result of 3D-BASIS are identical (refer to Section 8 and Appendix B of NCEER 91-0005, Nagarajaiah et al., 1991).



■ **Figure 2**
Cross-section and isolator layout of lead rubber bearings in an isolated building



■ **Figure 3**
Comparison of analysis of 3D-BASIS and DRAIN-2D for lead rubber bearing isolated building

Liquefied Natural Gas (LNG) Storage Tanks

Two 6500 m^3 storage tanks were designed to store hazardous liquefied natural gas in an installation located in an area prone to severe seismic

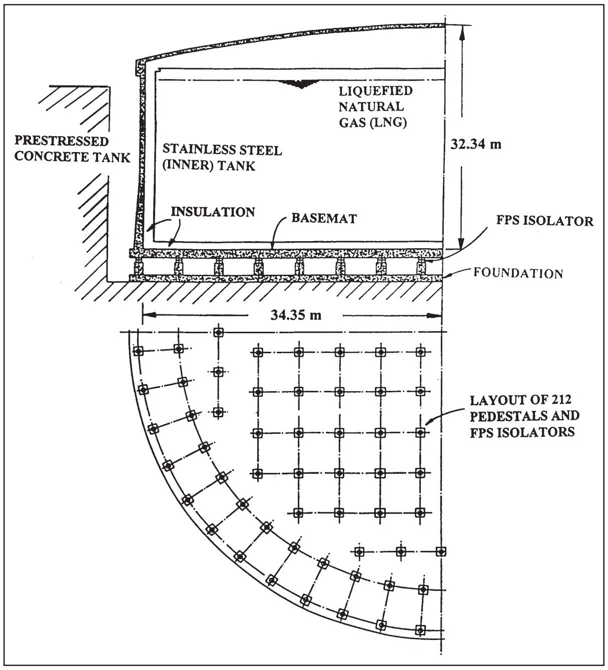


Figure 4
Cross-section and isolator layout for liquefied natural gas tanks

activity in Greece. Each tank is supported on more than two hundred sliding bearings of the type of friction pendulum system, which were previously used in the seismic retrofit of U.S. Court of Appeals. (See Protective Systems for Buildings: Application of Spherical Sliding Isolation Systems in this volume).The analysis and the design was done using 3D-BASIS-ME, which is capable of modeling the liquid structure interaction and the influence of the outside shell by three different towers as shown in figure 4. The design obtained and verified using local seismic data and the isolation models simulated modules were obtained with a small set of properties describing the tank components. Issues related to the influences of overturning moments and to the verification of friction forces as a function of the varying pressures, due to the influence of vertical earthquake components, were solved and indicated that these were extremely important to the design of the LNG tanks.

Conclusion

The 3D-BASIS program series has the capability to analyze buildings and bridge systems with complex isolation systems under three-dimensional earthquake motion. The program was structured to adapt and easily add new models of isolation systems without changing the numerical and analytical procedures. The natural expansion of this program series is the development of a complete 3D nonlinear analysis system (which currently is in progress within the highway research program at NCEER). The development of this program facilitated the expanding use of the base isolation in the United States.

Personnel and Institutions

This program involved many researchers and engineers in an interactive collaborative effort:

- The development of individual models for sliding isolation components and their verification was done in collaboration and with support of industries Watson-Bowman Company of Buffalo, New York; Earthquake Protection Systems of San Francisco, California; Aeroflex, Inc., of Long Island, New York; M.S. Caspe Company, San Mateo, California; Taisei Company, Tokyo, Japan; Taylor Devices, Inc., Buffalo, New York; and Sumitomo Industries, Tokyo, Japan.

- The research was done in an interactive collaboration with the members of the team at University at Buffalo and University of Missouri Columbia, with participants from University of Rome, University of Aachen, University of California, Berkeley, Washington University (St. Louis) and others.

- Integration of base-structure complex systems was done in collaboration with ZSEIS, Inc., of Virginia.

■ The program was verified and redesigned following interaction with government organizations, i.e., OSHPD/Sacramento; California, Caltrans, Sacramento, California, and private consultants S.O.M./San Francisco, California; C. Kircher and Associates, San Francisco, California; John A. Martin and Associates, Los Angeles, California; KPFF/Los Angeles, California; and others.

■ The computer program series was used as an educational aid in a bi-annual graduate course for design of base isolations, at the University at Buffalo and the University of California at Berkeley, that educated engineers currently involved in design of large retrofit and new construction projects.

■ The use of this program in practical applications gained rapid expansion. Several projects are noteworthy:

(1) Retrofit of the U.S. Court of Appeals in San Francisco, California (see figure 1) a historical building about 100 years old of 350,000 sq. ft., previously damaged in 1906 San Francisco and in 1989 Loma Prieta earthquakes, was retrofitted with more than 250 pendulum friction sliding bearings.

(2) Construction of Emergency Response Building (911) in Los Angeles, California. A building of ccc. 30,000 sq. ft. was designed and constructed using 28 elastomeric bearings.

(3) New Los Angeles County Martin Luther King Hospital, Charles R. Drew Trauma Center, a 200,000 sq. ft. building was constructed using 70 high damping rubber bearings and 12 sliders. The design was verified using 3D-BASIS by the regulatory government agency (construction in progress).

(4) A new facility for San Bernadino County Medical Replacement Facility, a complex of 840,000 sq. ft. was designed with 400 elastomeric bearings and 1233 viscous fluid damping devices. The design was done using 3D-BASIS series based on models developed in experimental studies (many at NCEER/University at Buffalo Laboratory) (construction started).

(5) New facilities are in design stages, with the design based on 3D-BASIS support, such as new Los Angeles County/University of Southern California hospital, a $250 million dollar base isolated facility, the retrofit of Los Angeles City and of San Francisco City Halls using elastomeric bearings and complementary damping devices.

■ A new group was established to provide a two-way interaction with the final users, support their activities and feedback important applicative issues (which already made their way in current research programs, such as stability of isolation and structures, uplift, and other topics).

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