Theses: IIT Bombay

Doctor of Philosophy

Earthquake Behavior and Impact Response Control of Base-Isolated Buildings
[Matsagar Vasant Annasaheb; 2005; Supervised by R. S. Jangid]

The base isolation technique has been used successfully worldwide in many buildings and other structures for earthquake protection. Although behavior of isolated buildings is satisfactory during earthquakes, the large displacements at isolation level remain the foremost disadvantage. Due to insufficient or improper separation gap distances provided or occurrence of stronger than predicted/ design earthquake, especially at near-fault locations, the base-isolated buildings may collide upon the adjacent structures. Such impacts may call upon catastrophic failures, despite the isolated structure function satisfactorily without such events. Therefore, it is imperative to investigate the response of base-isolated buildings to the impact with the adjacent structures. Fundamental working principle of base-isolated structures is explored here using analytical shear beam model and discrete two-dimensional and three-dimensional models. Further, the behavior of isolated building and influence of the shape of isolator force-deformation loops on its response is studied, which revealed necessity to adopt appropriate mathematical modeling of isolation. The superstructure flexibility and isolator characteristics are crucial factors in the design of base-isolated buildings. The effects of torsional coupling, due to isolator parameters such as the isolation stiffness and/ or yield strength, on the seismic response of base-isolated buildings are computed along with the other sources of asymmetries. The torsional couplings due to dissimilarity in the isolator properties considerably influence the seismic response of the base-isolated structures. The dynamics of impact problem in base-isolated buildings is studied through closed-form solutions for shear beam model, wherein free-vibration and earthquake-induced forced-vibration analyses are carried out without presuming the parameters of impact phenomenon. In addition, the seismic response of multi-story base-isolated symmetric and single-story asymmetric buildings during impact with the adjacent structures under earthquakes is presented. It is found that such impact events reduce the effectiveness of isolation to a greater extent. Performance of various isolation devices used in practice categorized as elastomeric and sliding systems is compared during impact condition. The mitigation of impact failures is suggested by improvising the base-isolated structures, introducing dampers for energy dissipation and seismic response control. The adjacent buildings to the base-isolated one are connected through viscous or visco-elastic dampers. The usefulness of such damper linkages in mitigation of seismic response is established through parametric studies.

Seismic Performance Enhancement of Bridges
[Madhusudan Dhananjay Chaudhari; 2005; Supervised by Alok Goyal]

The isolation and energy-dissipating devices are increasingly used to correct or regularize the expected response by adding flexibility to stiffer pier, dissipating undesirable input energy and thus avoiding possible concentration of ductility factor demand in bridge piers. For expected performance, design of isolation and energy-dissipating devices requires rigorous characterization of anticipated ground motions. Additionally, computationally efficient procedures are required for the performance evaluation of the designed bridges if they are to be fitted with isolation and energy-dissipating devices. All existing isolation systems have limitation in controlling the desired performance and therefore, an improved isolation system has been proposed that is simple to manufacture and easy to implement in existing or new bridges. A systematic procedure is presented in the thesis to select ensembles of recorded acceleration time histories from the available database of earthquake parameters (moment magnitude range, epicentral distances and local site conditions), and structural response parameters (design pseudo-acceleration response spectrum ordinates and ductility factor demand) for various limit states. For the performance evaluation of an existing bridge, a detailed mathematical model is presented. The formulation of equations of motion has been done using substructure method for the deck, the bearings and the piers. The presented procedure has the flexibility of modifying the model for any substructure as well as incorporating any kind of non-linearity in the bearing or introducing sliding systems in the analysis. Guidelines have been presented to convert the complex system to an equivalent SDOF system for the selection and evaluation of effectiveness of an isolation system. A number of isolation and energy-dissipating devices that are being increasingly used to correct or regularize the expected response have been investigated. Compared to the existing isolation system, the performance of newly proposed VFPI system is superior though experimental verification is far less extensive. Each existing system has its advantages and limitations in controlling the seismic performance and therefore, a combination of sliding surface mounted on laminated rubber bearings has been investigated for the improved performance. The proposed isolation system uses the combination of low-stiffness high-damping laminated rubber bearings and two-material flat sliding surface mounted on high-stiffness low-damping laminated rubber bearings. The proposed system is simple to manufacture and easy to implement in existing or new bridges. The designer has maximum flexibility in the selection of dimensional and friction parameters to control the response for non-seismic operational loads, for both moderate intensity and high intensity ground motions. The system has the capacity to dissipate a large amount of energy while maintaining a pre-defined restoring force. It has been demonstrated for eighteen acceleration time histories that the proposed system can be effectively used to enhance the seismic performance of bridges to the desired level for a wide range of frequency contents and intensity levels of expected ground motions. The proposed system is simple but requires a higher level of engineering skills for the selection of parameters. To overcome this difficulty, a simple design procedure has been developed and presented for the selection of most efficient parameters based on performance requirements.

Earthquake Response of Multistory Framed Structures with External Viscous Dampers
[H. R. Prabhakara; 2005; Supervised by Alok Goyal and Ravi Sinha]

The damaging effects of destructive earthquake forces can be reduced by using modern structural protective systems. The earthquake performance of structures can be improved to desired level using specially designed supplemental energy dissipating devices. Viscous, viscoelastic (VE) dampers are the simplest energy dissipation devices from practical considerations as they can be used to retrofit an existing building without disruption of functional use. In a torsionally coupled building, torsional modes are also excited due to lateral ground motion. If in an existing building, torsional modes could be damped heavily and the damping in the lateral modes could be increased, the demand of strength in vulnerable elements of the structure could be significantly reduced. For a fixed configuration of VE dampers and their energy dissipation capacity in terms of damping coefficient, modal strain energy or equivalent methods need to be developed and experimentally verified to predict the equivalent structural damping in structures with VE dampers. In the present study, the effects of supplemental damping provided by linear viscous dampers in controlling the response of multi-story torsionally coupled frames have been investigated. It has been demonstrated both experimentally and numerically that the response of a framed structure may be reduced to desired level by providing external dampers for supplementing energy dissipation. The reduction of response depends on the amount of energy that can be dissipated through these external dampers. One can use less number of dampers with higher damping coefficient or a larger number of dampers with smaller damping coefficient. From design point of view, it is sufficient to increase damping in the first lateral modes in two orthogonal directions using VE dampers. It has been demonstrated that the lateral drift and floor rotation of the soft story is effectively reduced by providing external VE dampers in the soft story. This provides an exciting alternative for retrofitting of the existing structures with soft story. Based on the experimental and numerical investigations, design criteria to reduce the response of real framed structures utilizing supplemental energy dissipating devices in the form of external VE dampers has been suggested. Due to inherent uncertainties in the properties of external VE dampers, it is recommended that external dampers be symmetrically placed wherever possible.

Seismic Response of Isolated Liquid Storage Tanks
[M. K. Shrimali; 2003; Supervised by R. S. Jangid]

Failure of various liquid storage tanks directly supported on ground and few elevated tanks during recent earthquake had generated lot of interest to safeguards the tanks against seismic forces. Conventionally strengthening of tanks does not ensure absolute safety of a liquid storage tank during strong earthquake ground motion. The other technique to protect liquid storage tanks is base isolation which is also known as aseismic design. The isolation technique has developed the interest among researchers and same has been implemented in buildings and bridges. In the present study, research work done in area of seismic analysis of ground supported and elevated liquid storage tanks as well as different isolation techniques developed have been reviewed. A comprehensive parametric study on ground supported cylindrical liquid storage tanks seismically isolated by elastomeric (with and without lead core) and sliding bearings has been investigated. The important parameters considered are: isolation time period, damping, yield strength of bearing in N-Z system, velocity dependent friction coefficient of sliding system and aspect ratio of tank. This important investigation revealed that the need of appropriate selection of isolation parameters for the design of base-isolated tanks. The study of bi-directional excitation of base isolated tank leads to interaction of restoring/frictional forces which is crucial from bearing displacement view point. In addition to the above study modal response of the base-isolated ground supported tank is carried out. The investigation indicates that the seismic response is influenced by a particular mode. The most convenient and practical response spectrum method predict the result fairly accurate to be used in practice. An approximate method is developed to investigate the response of the tanks considering linear behaviour of the isolation system. The modal parameters predicted by the approximate method matches with the corresponding exact parameters. The seismic response obtained using the derived modal parameters matches with the exact response. Therefore, the approximate method which is computationally more efficient predict the response of the isolated tanks accurately. The response of elevated liquid storage tank isolated by linear elastomeric bearing is investigated and found that the isolation is effective. The two tank models considered by placing the base isolation system at the top and bottom of the supporting tower structure predict the identical results. A simplified model of isolated elevated tank is also proposed by assuming the rigid body motion of the tower structure and impulsive mass. The response of the proposed approximate method closely matches with the exact response.

Earthquake Response of Seismically Isolated Bridges
[Nitin P. Tongaonkar; 2001; Supervised by R. S. Jangid]

It is a well-known fact that the strength alone will not ensure the safety of a bridge during a strong earthquake like Kobe (1995). As a result, an alternate approach using base isolation for aseismic design of bridge structures is explored in this report. Comprehensive numerical studies are carried out to investigate the behaviour of seismically isolated three span continuous deck bridges with different type of piers and seismic isolation devices subjected to bi-directional earthquake motion. Various isolation systems considered include elastomeric bearings (with and without lead core) and sliding isolation device (with and without restoring force). The earthquake ground motion is applied both in longitudinal and transverse directions modelled both as deterministic as well as stochastic. For deterministic analysis three recorded earthquake ground motions (i.e. El-Centro, 1940; Northridge, 1994 and Kobe, 1995) are used. The governing equations of motion of the isolated bridge system by duly considering bi-directional effects are derived. The response of the system is obtained by numerically integrating the equations of motion since the force-deformation behaviour of the system is non-linear. In order to study the effectiveness of isolation system the response of the isolated bridge is compared with corresponding response of non-isolated bridge. A parametric study is conducted to investigate the effects of important system parameters on the effectiveness of isolation. The important parameters include flexibility of bridges, time period, damping ratio and friction coefficient of isolation devices. It was found that the seismic isolation is quite effective in reducing earthquake response of bridges. This technique is found to be more effective for stiff bridges as compared to flexible bridges. In addition, the bearing flexibility and damping ratio influence the response of the system. There exists an optimum isolation damping for which deck acceleration and pier base shear are minimum. It is also observed that interaction of bearing restoring forces significantly influence the bearing displacements and ignoring these effects will underestimate the isolator displacements. Further, the performance of elastomeric bearing with lead plug is found to be better as compared to other devices. The effects of soil structure interaction on the response of seismically isolated bridges with elastomeric bearing are also investigated. It is found that the SSI effects significantly influence the response. By ignoring these effects the displacements of bearing at abutment will be underestimated which can be crucial from the design point of view.

Seismic Control of Structures Using Tuned Liquid Dampers
[Mohan M. Murudi; 2001; Supervised by P. Banerji]

Tuned liquid dampers (TLD) are energy-absorbing devices that have been proposed to control the dynamic response of structures for wind loads. These devices are simple to construct and maintain, and have been implemented in practical structures for wind response control. There has, however, yet been no comprehensive study that investigates the effectiveness of a TLD for seismic vibration control and gives guidelines for design of such a TLD. The main objective of this study is, therefore, is to investigate the effectiveness of a TLD for earthquake loads.

The TLD used here is a rectangular tank partially filled with water to a shallow depth. A non-linear water wave theory, that has been proposed and experimentally verified in earlier studies, is used to idealise the water motion in each TLD. Only numerical simulations are done in this study. An attempt is made to define proper design parameters of various TLD systems for them to be effective in controlling the earthquake response of a structure. The effects of various ground motion parameters on the TLD performance in controlling structural response are also investigated. Furthermore, an alternate configuration called a Tune Mass Liquid Damper (TMLD), which works on the principle of amplification of TLD base motion through secondary structure, has been proposed to improve the effectiveness of a standard TLD in controlling earthquake response of structure.

Results show that a properly designed TLD can significantly reduce the structure's response to broad-banded earthquake motions. In fact, the TLD has a desirable property in that it is more effective in reducing structural response as the ground excitation level increases and for structures whose responses are large for a given earthquake. Comparison with results from earlier studies show that the TLD is potentially better for earthquake response control than the TMD and TLCD devices proposed by others. A MTLD system, with optimum parameters, is shown to be slightly more effective and more robust than a single TLD for earthquake motions, especially for larger ratios of water-to-structure mass. Finally it is shown that a properly designed TMLD is significantly more effective than a standard TLD in controlling earthquake response of a building structure.

VFPI: An Innovative Device for Aseismic Design
[Pranesh M.; 2000; Supervised by Ravi Sinha]

Safety of important structures and critical facilities during earthquakes is of great importance and is an area of active research. Traditionally, safety of the structures has been enhanced by making their members stronger and more ductile, so that they can withstand higher forces. However, these structures experience limited and controlled damage to dissipate the earthquake energy. This may lead to loss of functionality or other serviceability problems. An alternative approach that is gaining popularity is to reduce the earthquake energy that is introduced into the structure. Base isolation uses the latter concept, wherein a flexible layer is introduced between the structure and its foundation. Base isolation systems increase the fundamental period of the structure in order to move them away from the predominant periods of excitation. The energy spectrum of earthquake ground motions at long periods is typically a fraction of its maximum value occurring relatively at shorter periods. Base isolation is thus able to reduce the maximum energy that is introduced into the structure. One of the most effective base isolation techniques is to introduce a sliding layer between the structures and its foundation. The ability to slide in these systems provides isolation, while the frictional force also dissipate energy further reducing the energy introduced into the structure. Sliding isolators have been found to be relatively insensitive to ground excitation characteristics. In this thesis, an analytical framework to evaluate the response of a structure isolated by a sliding type isolator having a curved geometrical profile has been developed. The formulations use the complex modal analysis to consider the effect of non-classical damping in the isolated structure. Closed form expressions have been developed for the response evaluation of the isolated structure subjected to deterministic ground motion. A thorough investigation of existing sliding isolators has been carried out to evaluate their effectiveness under different conditions. However from the investigations in this research work it has been found that these isolators have serious limitations that hamper their effectiveness in controlling the vibrations. In the present investigations these limitations have been clearly brought out through extensive analytical and numerical simulations. A new isolator called as Variable Frequency Pendulum Isolator (VFPI) that overcomes the major limitations of the currently used friction-type isolation systems has been developed in the thesis. The concept of VFPI is based on the idea that the disadvantages in the friction-type isolators can be minimised by use of variable frequency and a restoring force softening mechanism. The effectiveness of VFPI under different parametric variation in comparison with the conventional friction systems has been investigated in detail to highlight the merits of the proposed isolation system. From the investigations it is found that the VFPI is very effective in controlling the vibrations in a structure due to ground motions for a wide range of the excitation characteristics. The performance of VFPI is independent of the characteristics of input excitation. The VFPI limits the energy transmitted to the structure (similar to a pure-friction isolator) due to its restoring force being bounded and also incorporates an effective restoring mechanism that will help the structure to come back near to its original position after an earthquake. So, the VFPI incorporates the advantages of other friction-type isolators. In the present investigations the effectiveness of VFPI has been evaluated for both simple single-degree-of-freedom (SDOF) models and also three-dimensional models. Based on the investigations on 3-D models it is observed that the VFPI is also effective in reducing the torsional response of the structure. The VFPI is also found to be effective in reducing the response of a secondary system supported over the isolated structure. Thus the VFPI incorporates the features of an ideal isolator and energy dissipator.

Earthquake Response of Above-Ground Pipeline System
[Aurobindo Ghosh; 1996; Supervised by P. Banerji]

Cross-country above-ground pipelines is one of the important utility system for transportation of oil, water etc. All modern countries where such pipelines are in use are not excluded from natural hazard such as earthquake. As these pipelines are in operation all through the year safety requirement for these pipelines to natural hazards like earthquake is called for. This thesis highlights the important aspects in view of earthquake ground vibration impact on above-ground pipelines.

In recent years various studies those are carried out focuses on the different modeling of pipelines for analyzing the pipelines to earthquake ground motion. Again there exists two types of pipeline model for analysis of above-ground pipelines and they are rigid segmented pipeline joined by flexible joints and the flexible continuous pipeline. As the name above-ground pipeline suggest the pipeline is essentially above ground. The pipelines are sometimes run well above the ground and hence a supporting structure come into picture. Such aspect of pipeline study in detail for earthquake response has not been carried out. So above-ground pipeline response to earthquake vibration has been studied here with pier.

In the work presented a pipeline modeling has been carried out considering pipeline as a 3D beam element in case of flexible continuous pipeline supported on piers and secondly rigid segmented pipeline joined by flexible joints and supported on piers. These piers in turn have footings resting on ground. So the pipeline system as considered here has necessarily three subsystems and they are pipe subsystem, the pier subsystem and the foundation subsystem. Earlier pipeline system does not include the pier subsystem that brings not only the elevation difference of the pipeline with ground but also the pier stiffness. As pipelines run into kilometers different parts of pipeline experience different earthquake motion because of the spatial effect of the ground motion.

Seismic Analysis and Design of Multistorey Frames under Ductility and Energy Failure Criteria

[Mahua Ajay Chakrabarti; 1996; Supervised by R. Ranganathan]

The aim of the present work is to carry out seismic analysis and design of multistorey frames under ductility and energy failure criteria. Three representative damage functionals are chosen for the study viz. the displacement ductility damage index, the Park and Ang damage index and the energy damage index. Using the three damage definitions, the damage indices are evaluated for a large number of single and multistorey frames under two representative earthquakes viz. the 69o south east component of the Taft earthquake and the north south component of the El Centro earthquake. From this study it is inferred that under seismic loads, the ductility failure criterion is inadequate and the energy as well as the combined failure criterion should be considered in order to ensure a safe design. Reliability analysis is next performed using the three damage based limit states with a view to check the variation in the probability of failure due to the three limit state formulations and it is observed that the energy failure criterion gives the largest probability of failure and the displacement failure criterion gives the smallest probability of failure, thus proving the necessity of evaluating safety of every design against the energy failure criterion. Three strategies to reduce a nonlinear multistorey frame into an equivalent nonlinear single storey frame are identified and employed in order to approximately calculate the energy dissipated by hysteresis under a given earthquake for a variety of five, ten and twenty storeyed frames. From this study, it is seen that these methods do not work well for frames whose response is governed by higher modes of vibration. The nonlinear response spectrum is also generated using the three failure criteria and it is observed that for a given earthquake, the base shear ordinates of the inelastic response spectrum based on the energy failure criterion are higher than the corresponding ordinates of the displacement failure based inelastic response spectrum but are lower than the elastic response spectrum ordinates. Using the base shear ordinates of the energy failure based inelastic response spectrum a seismic design method which yields safe designs against all the three failure criteria is proposed and demonstrated. A five and a ten storeyed frame have been designed and evaluated against the two representative earthquakes. This design is economical as compared to the design based on the elastic response spectrum since the base shear ordinate used for design is lower than the elastic base shear obtained.

Nonlinear Earthquake Response of Reinforced Concrete Stack-Like Structures
[Manoj Kumar Maiti; December 1995; Supervised by Alok Goyal]

A better understanding of the inelastic behaviour and actual seismic resistance of reinforced concrete stack-like structures is necessary to develop earthquake resistant design guidelines for such structures. The objectives of this investigation are: a) to develop reliable techniques for nonlinear earthquake analysis of reinforced concrete stack-like structures; b) to study their inelastic earthquake response; c) to develop procedures for estimating their inelastic seismic resistance in terms of macroscopic ductility factors (MDF); and d) to investigate the significance of different parameters on MDF so that reliable guidelines for design can be developed.

An incremental step-by-step finite element procedure is adopted for the nonlinear analysis. The stack-like structure is idealized as an assemblage of two noded beam elements that include axial and bending deformations. Material nonlinearity is included in the analysis by assigning material properties to each concrete layer and reinforcing steel bar from their idealized cyclic stress-strain relationships. Geometric nonlinearity is accounted for by continuously updating the nodal point geometry and the local to global transformation matrices of each element. Newmark's average acceleration scheme is used for time integration with equilibrium iteration in every step. An adaptive time-step reduction procedure is developed that reduces the computational efforts significantly.

Analysis of a typical stack-like structure for a scaled-up actual ground motion shows that the stack undergoes considerable yielding and plastic deformations, and remains stable in spite of being statically determinate. A significant part of seismic input energy is dissipated by hysteretic action, and displacements and self weight are not large enough to cause failure due to gravity effects after significant yielding of one section.

The MDF is computed by inelastic time-history analyses for an ensemble of simulated earthquakes and taking the average ratio of the ordinates of maximum sustainable earthquake spectra and elastic design strength earthquake spectra for the stack. Collapse criteria based on maximum compressive strain in concrete and maximum tensile strain in steel are used. Computed MDFs are presented for different parameters of stacks that can be used effectively in deriving the design spectra from the maximum credible earthquake spectra at a site. The ductility capacity of stack-like structures is much more than what had been expected in the literature, especially for stacks with lower axial force ratio. Shear forces in stacks during maximum credible earthquake are much higher than those for elastic design level earthquake. However, minimum codal requirements of circumferential reinforcements are sufficient to carry this increased shear in most situations. Estimation of maximum displacement during inelastic behaviour as a product of the elastic displacement for design level earthquake and the MDF, is unconservative mainly because of strain softening in concrete, and concentrated yielding in reinforcing steel.

Structural Idealization for Earthquake Response of Shear Wall Core System
[Adnan Fadih Ali Albasry; 1993; Supervised by P. Banerji]

A shear-wall core system typically consists of planar-walls or coupled-wall units interconnected to form a non-planar structure unit. The currently available idealization methods for analyzing these cores are: Discrete Element; Continuous Continuum; Finite Strip; Finite Element; and Analogous Frame approaches. These core structural idealization approaches demonstrate that no single approach, except the computationally-inefficient Finite Element, incorporates all significant factors that govern the behaviour of core systems when subjected to an earthquake ground motion.

Therefore, the primary objective of this study is: i. to develop an alternative method of shear-wall core idealization for analyzing earthquake response of any core, which would have a wider range of applicability than the Discrete Element idealization method, and applicable for all practical core configurations, and requires few d.o.f to represent the dynamic behaviour of the core; directly applicable to cores connected by lintel beams to other resisting elements; ii. to study the effects of beam depth variation on the dynamic response of perforated cores; and iii. to study the effect of shear and warping deformation on the dynamic response of shear-wall cores.

An idealization method designated as the Component Element (CE) method is proposed for such purpose. Essentially two different types of elements; (a) wall element, and (b) beam element, are considered as the basic components of the method. The wall element is based on the wide column analogy, with axial deformations, in-plane rotation, torsion and in-plane deformations of the wall are considered. The beam element is a modified standard plane beam element with one or two rigid arms incorporated at its ends. Beam response in-plane of floor slabs is neglected, that is, only lateral out-of-plane beam response is considered. Rigid floor slabs are accounted for by constraining all structure d.o.f in-plane of floors to be dependent on in-plane d.o.f of a master node defined at core center of mass, with translational d.o.f along the core longitudinal axis are not constrained, thus allowing warping of cross-section when the core undergoes torsional deformation.

The main conclusion drawn from the study, is that: A Component Element idealization method is developed for idealizing shear-wall cores, the method considers all significant factors that affect earthquake response behaviour of typical cores. The method has wider range of applicability than the (DE) method. Although the number of d.o.f needed to adequately represent the core behaviour in both methods is comparable, the main advantage of the (CE) method is that the cross-sectional properties need not to be computed, therefore, the method can be used to idealize all practical shear-wall core systems; The method provides computationally efficient direct analysis procedure for earthquake response of individual core components; other conclusion is that the presence of lintel beams highly affects the torsional behaviour of cores, therefore, the (DE) idealization method, which neglects these beams, underestimates overall torsional response of such cores. Shear and warping deformations are shown to be of significant effect in cases of squat cores and affect the torsional behaviour of these cores.

Structure-Foundation Interaction in Coupled Shear Wall Subjected to Earthquake Ground Motion

[Saher Raffat Ibrahim El-khoriby; 1992; Supervised by P. Banerji]

The influence of soil-structure interaction on the earthquake response of coupled shear wall systems is investigated. The coupled shear wall is idealized as an assemblage of discrete members that are modelled as modified frame elements so that finite width of shear walls, shear deformation in all members, and the localized deformation at inter-connecting beam-wall interfaces are considered. This structure is supported by a rigid footing on the foundation soil surface, which is idealized as a homogeneous, isotropic semi-infinite medium.

Effect of interaction parameters on response of coupled shear wall systems is studied, and it is seen that considering the effect of foundation soil flexibility on the first two fixed-base structure modes is important for these systems. However, currently available simplified methods of analysis consider only the effect of interaction soil flexibility on the fundamental mode. Therefore the effect of interaction on an equivalent two degree of freedom (2DOF) system that represents the two structure modes is studied. Based on this a simplified response history analysis procedure that considers the effect of soil-structure interaction on two structure modes is developed. It is shown that coupling between the individual single degree of freedom (SDOF) system in the equivalent 2DOF system can have a significant effect on the response of coupled shear wall system with shallow connecting beams.

An approximate response spectrum method based on the analysis of the equivalent 2DOF system is also developed here, which is suggested as a replacement of the current procedure that considers soil flexibility effect on fundamental structural mode only. An alternate response spectrum method based on a definition of equivalent modal damping in non-classical structure-soil system modes is also developed. From a study of force response estimates of an actual twenty six story shear wall building subjected to earthquake ground motion characterized by the 1952 Taft S69E acceleration time history, it is shown that the proposed approximate response spectrum methods compare favourably with "exact" response history analysis whereas the existing response spectrum method considering effect of soil flexibility on the fundamental mode only overestimates responses for some coupled shear walls.

Earthquake Analysis of Three Dimensional Shear Wall-Frame Assembly on Pile Foundations Considering Soil Structure Interaction
[Clifford D'souza; 1984; Supervised by D. N. Buragohain]

The earthquake response of a three dimensional shear wall-frame assembly on pile foundations considering soil-structure interaction is evaluated by the Frequency Domain General Substructure method (FDGS). The building-pile foundation system is treated as two substructures: building and pile foundation. For the building, the analysis incorporates the rigidity of floor slabs in their planes, the effect of three dimensional shear walls and the eccentricity of beam connections to shear walls. The concept of a floor node is introduced and the six displacements at a node are separated and associated with two nodes so as to enable a more efficient utilization of the frontal routine. The pile foundation is represented by means of impedance functions. Tremendous saving in computational effort is achieved by taking advantage of the following:

i) filtering out the higher frequencies of an earthquake record because of their low magnitudes;
ii) the symmetry and anti-symmetry of the Fourier transform of the earthquake record;
iii) the similarity of pile groups when assembling the frequency dependent impedance matrix of the pile foundation from the available impedance functions of a single pile.

A numerical example is solved to illustrate the above approach. A fifteen storeyed building with shear walls and supported on pile foundation is subjected to the longitudinal component of the Koyna earthquake of December 11, 1967. The earthquake is specified at the building-pile foundation interface and is uniform along this interface. Two different values of shear wave velocity of soil, Vs = 140 and 313 m/s are considered.

The results of this analysis are presented in graphical and/or tabular forms and compared for the two soil conditions to bring forth the effects of soil-structure on the response of the building. Soil-structure interaction results are more pronounced for the softer soil. The results show that there is a decrease in the response of the building as the soil becomes softer.

The maximum earthquake response of the building alone by assuming it to be fixed at its base is evaluated by the Response Spectrum method for Buildings (RSB) and compared with the absolute maximum response obtained by FDGS for the two soil conditions. The comparison with FDGS (313) shows that RSB is able to satisfactorily predict for design purposes the response of a building on relatively rigid soils. The comparison with FDGS (140) shows that RSB (critical damping ratio of 5%) gives highly conservative results for the response of the building on soft soils. For the softer soil case, the maximum earthquake response of the building considering foundation flexibility is also evaluated by the Response Spectrum method for Building-Foundation system (RSBF) by including the pile foundation. The evaluation of the mode shapes and natural frequencies of the building-pile foundation system for this purpose shows that these are not significantly different from those of the building on fixed base. This means that RSB can still be used for predicting satisfactorily the earthquake response of the buildings on soft soil provided a correct damping ratio is chosen. The assignment of a specific value for the critical damping ratio which must represent the damping of the building as well as of the pile foundation is, however, difficult and a few critical damping ratios, namely, 10, 20 and 25% are tried out with RSBF. Comparison with FDGS (140) shows that RSBF for a critical damping ratio of 25% gives satisfactory results.

Computer programs have been developed to carry out the different aspects of the numerical work.

It is believed that the results of this investigation bring forth the actual effects of soil-structure interaction in a building-pile system for the first time.