Session 1660

Development of Small-Scale Models for K-12 and Undergraduate Students to Demonstrate Earthquake Effects on Building Structures and Aseismic Design Procedures

Anant R. Kukreti
T. Michael Baseheart
University of Cincinnati

Abstract

This paper reports how several simple and portable demonstrations were developed which were geared toward educating and exciting Kindergarten through twelfth grade (K-12) students and college undergraduate students into the area of aseismic design. The need for more research and education in this area is evident with the massive destruction that continues to follow earthquakes all over the world. The paper first describes the basic experiments and associated equipment that can be used to quickly teach the principles of vibration. Second the paper describes the use of 1/24-scale building models to understand the basic principles of structural dynamics, and the use of dampers and base isolation devices as an aseismic strategy. These models can be used in a senior undergraduate structural dynamics elective course. The paper finally presents the features and use of structural dynamics models developed for K-12 students to provide them an exposure on effects of earthquakes on buildings. The paper also summarizes the learning experiences provided to the students who assisted in developing these models and experiments.

I. Introduction

Earthquakes are a constant source of both fascination and horror. Every few months there is another earthquake that rocks some unsuspecting population, usually with devastating results. The recent earthquake, of magnitude 7.9 on the Richter Scale, centered in the province of Gujarat, India left tens of thousands of people killed or injured and wiped out entire communities. In the city of Bhuj, nearly every building was destroyed from the earthquake. On the other extreme, the recent Nisqually Earthquake near Olympia, Washington had a comparable magnitude of 6.8 but resulted in only one death, from an earthquake related heart attack, and minor injuries numbering in the hundreds. There was also extensive damage to structures, but no total devastation. The difference in outcomes from these two earthquakes can be attributed to the use of aseismic design techniques. Aseismic design considers earthquake loading on structures and seeks to reduce the damage and loss of human life that may occur as a result of an earthquake. The main strategies of aseismic design are to employ various energy-absorbing and isolation devices. These devices reduce the vibrations that occur when structures are subjected to earthquake loads.

A major problem with earthquakes is that it is very difficult to tell when and where the next earthquake will strike. Researchers often rely on information from previous earthquakes to aid them. Small-scale structural models subjected to dynamic forces are also being used to test aseismic design techniques. Another aid in research and development of aseismic design strategies has come from the National Science Foundation (NSF). The NSF is funding the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES). The goal of NEES is to provide a national, networked collaboratory of geographically-distributed, shared-use next-generation experimental research equipment sites, with teleobservation and teleoperation capabilities, which will transform the environment for earthquake engineering research and education through collaborative and integrated experimentation, computation, theory, databases, and model-based simulation to improve the seismic design and performance of U.S. civil and mechanical infrastructure systems.

This paper reports how several simple and portable demonstrations were developed which were geared toward educating and exciting Kindergarten through twelfth grade (K-12) students and college undergraduate students into the area of aseismic design. These were developed by a group of three undergraduate students who participated in a NSF sponsored Research Experiences for Engineers (REU) Site during June 11 through August 3, 2001, and worked under the close supervision of the two authors of this paper. The students were from University of North Dakota, Grand Forks, North Dakota, University of Oklahoma, Norman, Oklahoma, and University of Cincinnati, Cincinnati, Ohio. Two of them were Civil Engineering students, and one was a Mechanical Engineering student. Since none of these students had taken any course on Vibrations or Structural Dynamics, an understanding of basic vibration principles was needed along with knowledge on how some general pieces of equipment commonly used for structural testing work. The experiments conducted to provide them this experience are described first in this paper. The students also needed to understand how experiments on scaled-models of building systems are conducted to measure experimentally their dynamic performance and to evaluate different asiesmic strategies for mitigating damage caused by earthquakes on buildings. The experiments conducted to provide them this experience are described second in this paper. With this knowledge gained the students developed three sets of hands-on experiments for demonstrations for K-12 students, which are described third in this paper. The paper ends with some concluding remarks summarizing the whole experience. Hopefully the experiences reported in this paper would assist others to plan similar experiments for both undergraduate education and for outreach education to K-12 students.

II. Experiments Illustrating Vibration Principles and Associated Measurement Equipment

The project was begun with the learning of basic vibration principles through literature that was provided to the students, and the help given by the two faculty mentors (authors of this paper), who worked closely with the students. First the topic of strain gages was discussed, as they play an important part in many of the measurement devices that were to be used by the participants. With this knowledge, the group began learning how to use the different pieces of equipment needed for the project. The first piece was the P-3500 Strain Indicator Box, which they used to measure the voltage change in the strain gages and then outputted as strain. To emphasize the use of the strain indicator box, they conducted a simple static strain experiment involving a cantilever bar with a varied point load applied at the free end. Strain gages were longitudinally attached to the top and bottom surfaces of the bar at a little distance away from the fixed end, and the leads of the strain gages were connected to the strain indicator box in quarter and half bridge connections. Known amounts of weight were then applied at the free end of the bar and the corresponding strain was recorded. When plotted, this showed that there was a linear relationship between weight applied and resulting strain. The group then learned how to use a Hewlett Packard 35660A Dynamic Signal Analyzer. Its use was emphasized with another simple experiment to determine the natural frequency of a cantilever bar. As in the previous experiment, there were strain gages longitudinally mounted on a cantilever bar and connected to a strain indicator box. The strain indicator box was connected to the dynamic signal analyzer and used to perform a fast Fourier transform as the cantilever bar was struck with a heavy object. This produced a graph with distinct peaks that could be paused and read. The reading from each peak represented a different natural frequency for the cantilever bar. Knowing these frequencies the bar could be excited to any desired frequency using a LDS Barrel Exciter to observe the mode shape corresponding to this frequency. In this experiment the dynamic signal analyzer also operated as a function generator and was used as a source to produce sine waves for the barrel exciter. The sine waves produced were not very strong and were therefore amplified before reaching the exciter. By positioning the barrel exciter beneath and close to the fixed end of the cantilever bar, it was then excited at several of its predetermined natural frequencies and the various nodes (points along the bar which experience no vertical displacement) of vibration were observed. Thus, this experiment provided an opportunity to the students to observe various modes of vibration of a continuum. An extensive amount of time was also committed to the understanding of a Data Acquisition System (DAS). The DAS consisted of BNC 2080 and SC-2043- collection boards that were externally wired for their protection. The data could then be analyzed in real-time for the frequency content on the computer software Virtual Bench. The group also learned how to use an Electro-Seis Model 113 Shaker. This shaker was used for small-scale model testing and is designed to subject structures mounted on its table top to base motion with different sinusoidal frequencies. The sinusoidal frequencies were supplied by the dynamic signal analyzer and amplified. A PCB Accelerometer was used in many of the demonstrations to measure different natural frequencies with the aid of the dynamic signal analyzer.

III. Experiments and Models for Demonstrations to Undergraduate Students

In this phase of the project the students conducted six experiments on 1/24-scale one- and two-story small-scale building models to explore their use: to experimentally determine their frequencies, mode shapes and damping characteristics; and to compare different damping devices and base isolation techniques to improve the capabilities of the model to better withstand seismic loading effects. The models used consisted of four spring steel columns for each floor which have fixed connections at the base and a large steel block mass for each floor. The floor masses consisted of steel and the base mass of aluminum. A schematic view illustrating the different components of one- and two-story building models is shown in Figure 1, and a photographic view of the models is shown in Figures 2. The effectiveness of the following three types of dampers was explored: viscous, friction and beam yielding. Cylindrical rubber mounts are commonly used as supports in mechanical machinery to reduce the damage caused by vibration, and different size mounts are commercially available. To study the use of such mounts as base isolators for aseismic design, experiments were conducted with three different size diameter rubber mounts installed under each column of the model frame so that the model is decoupled from the shake table over which it is mounted. A schematic sketch illustrating how the base isolators were configured in the models is shown in Figure 3. The shake table is forced to move horizontally simulating the ground motion caused during an earthquake. To conduct these experiments, an assortment of pre-fabricated parts of models representing different story heights, different types of damping devices and commercially available base isolators were made available to the students. The models were also mounted to the shake table with and without base isolators to compare the effect of decoupling of the model from the seismic motion source. In all the experiments, data collection, processing and display of results in real time was automated using a computerized DAS and the commercially available software Virtual Bench to process and display the data procured.

In the first experiment the students conducted static load tests to determine the stiffness of a one-story model, conducted free vibration tests to experimentally determine the natural frequency of vibration of this model, and then compared their results to those obtained from theory to investigate how good their model performed.

The second experiment was similar to the first one except a two-story model was used. The stiffness of each story was computed by deflecting each story one at a time and holding the other one fixed, and the two frequencies of the structure were obtained by deflecting the floor masses to correspond to the theoretically computed first and second mode shapes. The students used two electromagnets to pull the floor masses by a known displacement and to release both the floor masses simultaneously using one electric switch. This was a challenging task, and they were successful within reasonable error limits.

In the third experiment, different type of dampers were installed, one by one, in the one- and two-story models of the first and second experiments. The damping coefficient for the frame was determined, and the effect of different damping devices on frequency and response was compared to that obtained for the undamped model. The amount of damping in each device was varied to investigate its effect on the response, for example in the viscous damper following three different fluids were filled in the damping device: water, ordinary cooking oil and motor oil. All results obtained for these three experiments were compared to those obtained from theory, and they compared very well (about 10% difference). It was found that though the friction damper and beam yielding damper reduced the motion the most, but the viscous damper produced a more smooth reduction in the displacement response. The beam yielding damper increased the natural frequency of the model, since it acted as a structural element and thus increased the model stiffness. A photograph of the free vibration experimental set-up for a two-story model with damping devices is shown in Figure 4. This figure also shows the two electromagnets used to pull the floor masses by a known displacement and then released simultaneously to make them vibrate freely.

The next three series of experiments involved mounting a one- and two-story model on a shake table, and subjecting it to a harmonic base motion. The tests were repeated for different base motion frequencies, and one of the frequency chosen for the base motion was close tot he natural frequency of the model. In the first experiment, the response of the bare model was measured, and in the second experiment the three damping devices were mounted on the model, one-by-one, and the response for each was recorded and compared to that obtained for the undamped model. The beam yielding damper was found to be the most effective in decreasing the amplitude of the displacements, whereas the viscous damper had a lesser, but smoother effect. The friction damper behaved very differently, at a base motion frequency which was much different than the natural frequency of the model. The friction damper did not let the model displace relative to the shake table because of the large static frictional force created, but as the two frequencies were made to approach each other (i.e., when resonance occurred) the model vibrated randomly by intermittently stopping and then starting with a jerking motion. A photograph of a two-story model mounted on the shake table is shown in Figure 5.

In the third experiment of the second series of tests, the one- and two-story model was tested on the shake table with and without base isolators. As stated earlier, three different diameter cylindrical rubber mounts were used, each having the same height. The largest size base isolators had very large vertical and horizontal (i.e., shear) stiffness, and so produced a response very similar to the model with the fixed base. The smallest size base isolators, on the other hand, produced a rocking motion, indicating that they had low vertical stiffness. The mid-size base isolators performed the best, they possessed high enough vertical stiffness to limit rocking, and adequate horizontal flexibility to effectively dissipate the energy of the base motion and to reduce the top-story horizontal displacements. Overall, the performance of the base isolators was better than the dampers.

The experiment conducted to determine the stiffness of a model showed that if all variables are fixed and only the column height is changed, the stiffness decreases with an increase in height. The free vibration experiment then showed that the natural frequency of the structure decreased as the stiffness decreased. The addition of dampers to the model had varying effects on the characteristics of the free vibration of the model. The friction dampers had increasing damping properties as more friction was applied to the damping devices. Both the friction and viscous dampers had relatively little effect on the natural frequency of the frame model. This was attributed to the fact that they only resist motion of the model without adding stiffness. The beam yielding dampers had dramatic effects on the damping properties of the frame model. Since the beam yielding dampers increased the stiffness of the frame model they also shifted the natural frequency of the model to become higher.

IV. Experiments and Models for Demonstrations to K-12 Students

Using the knowledge gained form the experiments described in the previous two sections, the REU participants then developed and constructed three distinct demonstrations for K-12 students. These demonstrations included lumped mass models, a fluid tank model, and a portable shake table, each of which are described in this section.

The lumped mass model basically consisted of a steel/aluminum cylindrical solid mass piece screwed to one end of a 1/8 in. diameter rod, and the other end of the rod was rigidly connected to a wood block. The lumped mass models were an additional simplification of the 1/24-scale models described in the previous section, as illustrated in Figures 6(a) and 6(b). These are intended for physical observation only. In the lumped mass model shown in Figure 6(b), the rod represents the building columns, and the cylindrical lumped mass represents the rigid top floor. Both the models shown in Figures 6(a) and 6(b) are actually idealized as a spring-mass system model shown in Figure 6(c) for mathematical analysis. In all the three models shown in Figure 6, the mass M has one degree-of-freedom and can vibrate horizontally. The stiffness K represents the stiffness of the column(s), which can be experimentally or theoretically determined from the following formula: $K = 12EI/L^3$, if the top end of the column does not rotate, and $3EI/L^3$, if the top end of the column does rotate. In these formulae E = modulus of elasticity of the column material, I = moment of inertia of the column cross-section, and L = clear height of the column. If perfect similitude rules can be developed for scaling both the geometric dimensions and material properties (mass density, modulus of elasticity, etc.) for simplifying from an actual building to a scaled model shown in Figure 6(a), and then further simplifying it to the demonstration model shown in Figure 6(b), the dynamic response results obtained by experimentally testing them will not be far apart. Also, the experimental results have been shown to match fairly well with those predicted by the mathematical model shown in Figure 6(c). The success to reproduce results from small-scale models that are representative of the actual prototype (full-scale) lies in the design and fabrication of the small-scale models that follow laws and theory of similitude within a reasonable degree of accuracy. Whereas, such similitude laws and theory were not exactly used in this project in designing the proposed demonstration model for a building (Figure 6(c)), but it was expected to be a good representative of the actual system to demonstrate vibration principles and how buildings behave when subjected to ground (or base) motion caused by earthquakes.

To verify that the lumped mass model performed as expected, the REU group also correlated the lumped mass model measured frequencies to those obtained from theory which assumes that the rod represents a column of a building in which the top end is fixed to a rigid floor mass and bottom end is fixed to the rigid foundation. Since at the top end of the lumped mass model a steel/aluminum mass was attached, it experienced some end rotation during vibration. To account for the changed end boundary conditions, the group developed a scaling factor between the model and theoretical results, and showed that this scaling factor produced reasonable results (within 10% variation) when they changed the model lumped mass as well as the model rod height (i.e., changed the column stiffness). Thus, they learnt how models can be calibrated to represent the real system.

The lumped mass models were designed to mount on top of a shake table, so that they could be excited by different sinusoidal base frequencies. As mentioned earlier, the models consisted of threaded metal rods to which metal weights could be attached. There were three distinct lumped mass model demonstrations developed, which included the variable mass, variable stiffness, and variable story models. The variable mass model consisted of three different mass weights, all mounted at the same height, on a wooden block, as shown in Figure 7. This model demonstrated that by varying the floor mass, the natural frequency of the structure could be altered. The variable stiffness model consisted of three identical weights, mounted at three different heights, as shown in Figure 8. This model demonstrated that by varying the column height, the natural frequency of a structure can be altered. The variable story model consisted of a structure with one mass at the mid level and another at the top (two stories) and a separate structure at an intermediate height, as shown in Figure 9. This model demonstrated the effects that an additional lumped mass can have on a system. The two-story model showed two natural frequencies, as opposed to the single natural frequencies of all other models. For each lumped mass demonstration, the natural frequency of each of the lumped mass model mounted on the wooden block was measured first using an accelerometer and dynamic signal analyzer. Then the wooden block was mounted on top of a shake table and was subjected to base motion. The frequency of the base motion was varied, one-by-one, to match the fundamental natural frequency previously measured for each of the lumped mass model mounted on the wooden block. When subjected to their base motion which had the same frequency as the natural frequency of the lumped mass model, it was observed that resonance developed and vigorous vibrations occurred in that model only. When the lumped mass model was excited at frequencies other than its natural frequency, there was relatively little movement. A photographic view of the variable stiffness model mounted on a shake table in Figure 10. Thus, these sets of three experiments demonstrate the following:

1) Each building has its own natural frequency, which changes with change in building's floor mass and column height (or stiffness).
2) The number of natural frequencies depend on the number of story heights. A one-story building has one natural frequency, whereas a two-story building has two natural frequencies.
3) Each natural frequency corresponds to a particular displaced configuration of the floor masses relative to each other, which is known as mode shape. For a two-story lumped mass model, if the model is excited to its first frequency (lower one) both the floor masses will move in the same direction at any instant, whereas if excited to its second frequency (higher one) the two floor masses move in

opposite direction at any instant. So each mode shape has its own frequency. The lowest natural frequency is referred to as the fundamental natural frequency of the model.

4) The ground (or base) motion cause by an earthquake also has its own predominant frequency. Maximum damage by an earthquake occurs in buildings in which the natural frequency of a building matches with the predominant ground motion frequency.
5) Higher frequency earthquakes can force a building to vibrate in a higher mode shape.

These are important and complex concepts in structural dynamics and earthquake engineering that can easily be introduced to K-12 students through these simple demonstrations.

Figure 11 shows a water tank model mounted on the shake table to demonstrate on an exaggerated scale the profile of the ground during a sinusoidal type ground motion. The tank is made of Plexiglas® and filled halfway with colored water for easy viewing. The tank is rigidly attached to the top of the shake table. When the shake table is made to vibrate, this demonstration gives an exaggerated depiction of the ground motion. The fluid tank model was mounted on the shake table and excited at varying frequencies to give a visual representation of ground motion profile during an earthquakes. This simple experiment demonstrates how the ground motion profile changes over a range of frequencies. Results from such an experiment are shown in Figure 12. Figure 12(a) shows the profile that results at about two hertz base motion frequency. It can be easily compared to a C-saw type motion observed in a children's playground. The speed at which the fluid surface wave moves is slow, but results in the maximum vertical displacement of the fluid in this demonstration. As the frequency is increased to about four hertz, two and three peaks in the fluid's surface movement are easily observed, as shown in Figure 12(b). This movement has an observed increase in speed (twice the speed of 2 Hz), but the vertical displacement begins to decrease (half the amplitude of 2 Hz).

To easily demonstrate the K-12 models a special portable shake table was designed and fabricated in-house, which was lighter and easier to transport than the shake table and equipment that was commercially available (Seis Model 113 shaker) and previously used. The shake table was so designed that both the lumped mass and fluid tank models could be mounted on it. Figure 13 shows a view of the potable shake table. As shown in this figure, for the table top, on which the models will be mounted, Plexiglas® is chosen. The Plexiglas® is transparent, giving the audience a clear look at how some of the parts of the shake table work. Two stainless steel shafts guide the tabletop, which are 0.5 in. in diameter. The driving mechanism that shakes the transparent table top is a motor connecting rod assembly, which appears behind the shake table top in Figure 13. A steel disk, approximately 0.5 in. in thickness and 4 in. in diameter is mounted to the motor shaft. A steel rod is connected to the movable shake table top at one end, and its other end is connected to the steel disk. The motor turns the disk along with one end of the connecting rod. This motion generates a back-and-forth motion for the movable table top, simulating the desired base motion. The steel columns of the lumped mass models are screwed directly into the transparent Plexiglas® table top, as shown in Figure 13.

The back and forth motion of the movable table top of the shake table is controlled by a DC controller wired to the engine. To vary the frequency of the base excitation the speed of the motor is increased or decreased. The distance of the end of the connecting rod from the center of the disk determines the amplitude of the vibration. Holes for mounting the connecting rod to the steel disc are drilled at different radii so as to give a greater variety of amplitude at which the movable table top can be excited. The simplification of the signal source and signal amplification from earlier methods, as well as a great decrease in weight and size, greatly increase the portability of this shake table.

V. Concluding Remarks

The authors strongly felt that with the constant threat that earthquakes provide and the limited academic courses offered on this subject, there should be an increased emphasis on education in this area. By introducing and exciting students of all ages into the area of seismic studies, they might be encouraged to pursue this area of study further. The need for more research and education in this area is evident with the massive destruction that continues to follow earthquakes all over the world. Important research contributions have been made in this area and are evident in the associated lower loss of human life in the event of such catastrophes, but many critical structures, such as hospitals and vital roadway structures, are still being severely damaged. By sparking interest in seismic design to students at an early age, it will ensure that solutions to the problems created by earthquakes will be solved. The experiences reported in this paper in teaching structural dynamics to engineering students suggest that if students could be motivated to study physical models along with the corresponding mathematical models, they would develop a much deeper understanding of the dynamic solutions, and also gain an appreciation of the implied assumptions of the mathematical models and how important deviations from these assumptions may be. An effective "erector set" concept of developing models is presented in this paper which consists of steel and aluminum plates to represent story masses, and spring steel strips of various lengths to represent columns of different building heights. Using the parts supplied for the “erector set” students can vary model properties without fabrication of new components. Multiple story masses can be clamped to tall spring columns to produce multi degree of freedom models. A more simplified “erector set” for K-12 demonstrations is also presented which consists of metal rods to represent building columns to which cylindrical steel/aluminum masses can be easily screwed to represent floor masses. These models can be mounted on a light weight shake table to simulate earthquake ground motion.

VI. Acknowledgment

The authors would like to acknowledge the financial support totaling $117,948 provided for executing this REU Site by NSF (Award No.EEC-0196371), and cost sharing funds totaling $10,000 provided by University of Cincinnati. Financial support totaling $7,500 provided by Dr.

Roy Eckart, Associate Dean for Academic Affairs, College of Engineering, University of Cincinnati to purchase the Seis Model 113 shaker, and the associated signal generator and amplifier, is also acknowledged. The authors would also like to acknowledge the following students who participated in the REU Site: Laith Hintz, Civil Engineering, University of North Dakota, Grand Forks, North Dakota; Danny Millobar, Mechanical Engineering, University of Oklahoma, Norman, Oklahoma, and Erin Thomson, Civil Engineering, University of Cincinnati, Cincinnati, Ohio. The authors would finally like to thank Mr. Robert E. Muench who served as the Lab Technician for the project, and the assistance he provided in fabricating the portable shake table.

ANANT R. KUKRETI

Anant R. Kukreti is a professor of Civil Engineering and Head of the Department of Civil and Environmental Engineering at University of Cincinnati. He was a faculty member at the University of Oklahoma for 22 years before moving to University of Cincinnati in August 2000. He has won numerous teaching awards, which include the Burlington Northern Foundation Teaching Award, Regents Award for Superior Teaching, ASEE Midwest Section Outstanding Teaching Award, and the ASEE Fluke Corporation Award for Innovation in Laboratory Instruction. At University of Oklahoma he also received the David Ross Boyd Professorship.

T. MICHAEL BASEHEART

T. Micheal Baseheart is an associate professor and Associate Department Head of the Department of Civil and Environmental Engineering at University of Cincinnati. He joined the department in 1973, and his contributions have been recognized within the university community and at the national level. He has won numerous teaching awards such as Neil Wandmacher Excellence Teaching Award in 1981 and 1996, and was elected as Educational Committee Member of the year in 1994 by the National Educational Activity Committee Board of the American Concrete Institute.

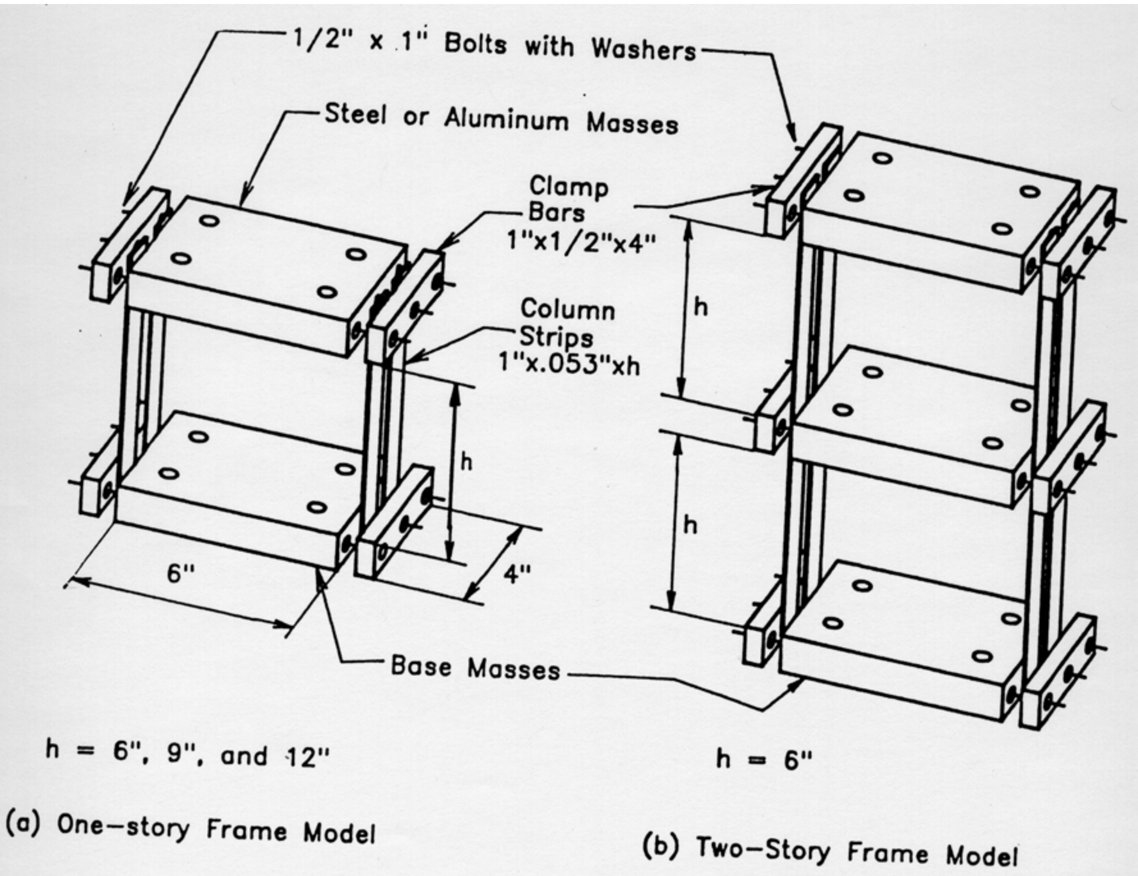
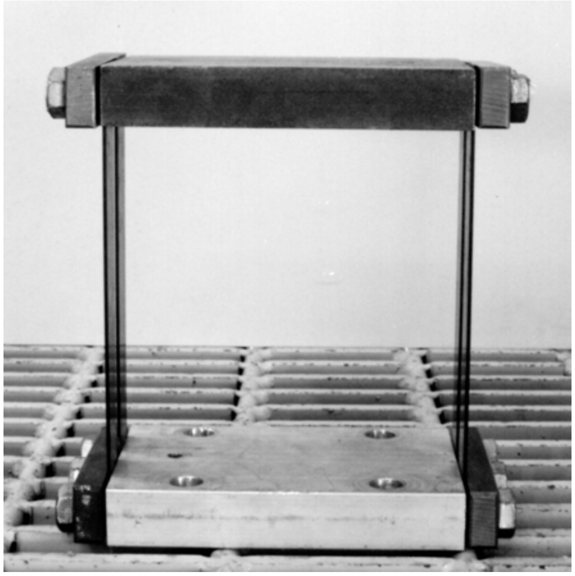
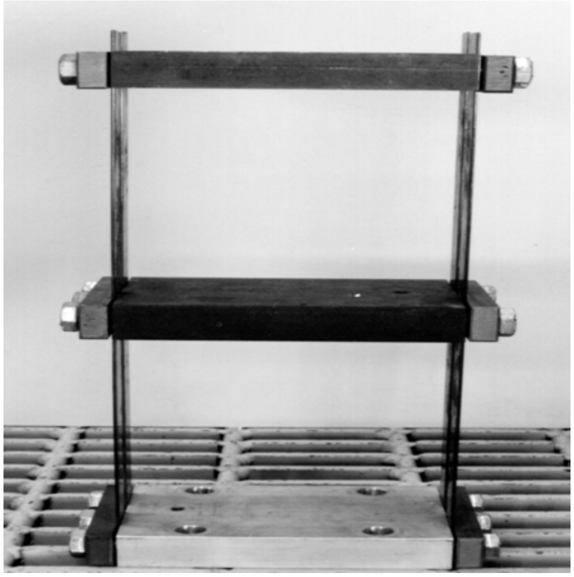


Figure 1. Schematic View of the Small-Scale Building Models



(a) One-Story Model



(b) Two-Story Model

Figure 2. Photographic View of Small-Scale Building Models

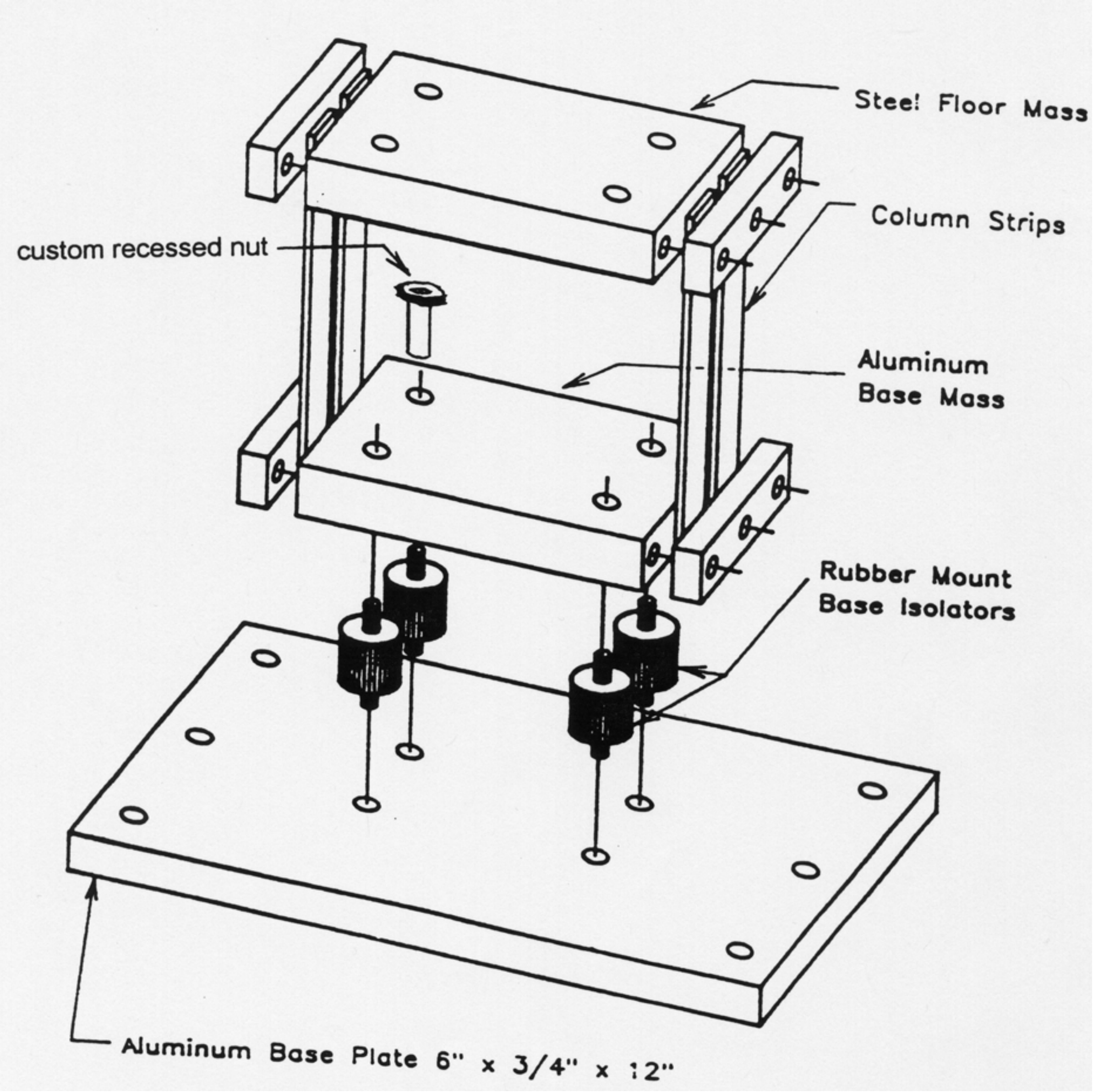


Figure 3. Schematic of Model with Base Isolators

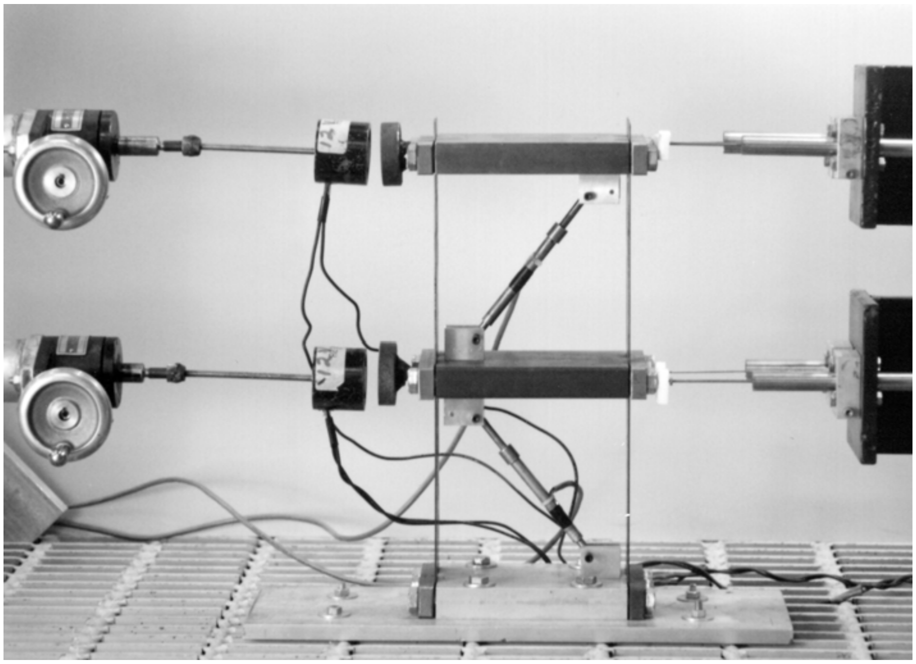


Figure 4. Photograph of Experiment to Determine Natural Frequency and Damping Parameters of a Two-Story Building Model with Viscous Dampers

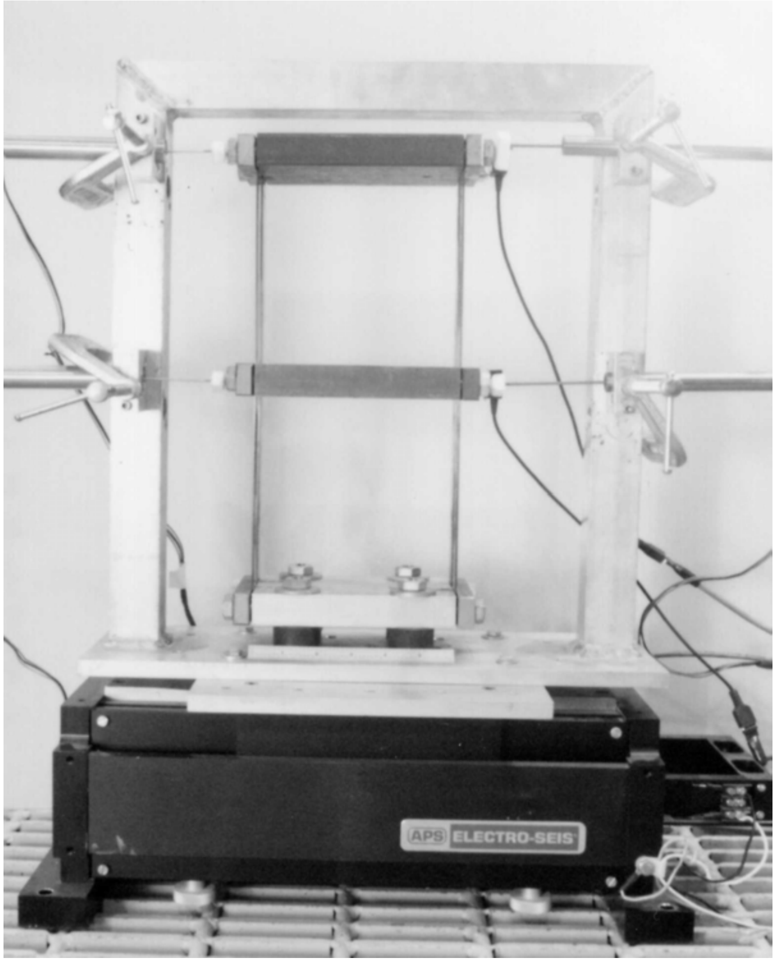


Figure 5. Two-Story Building Model Mounted on a Shake Table

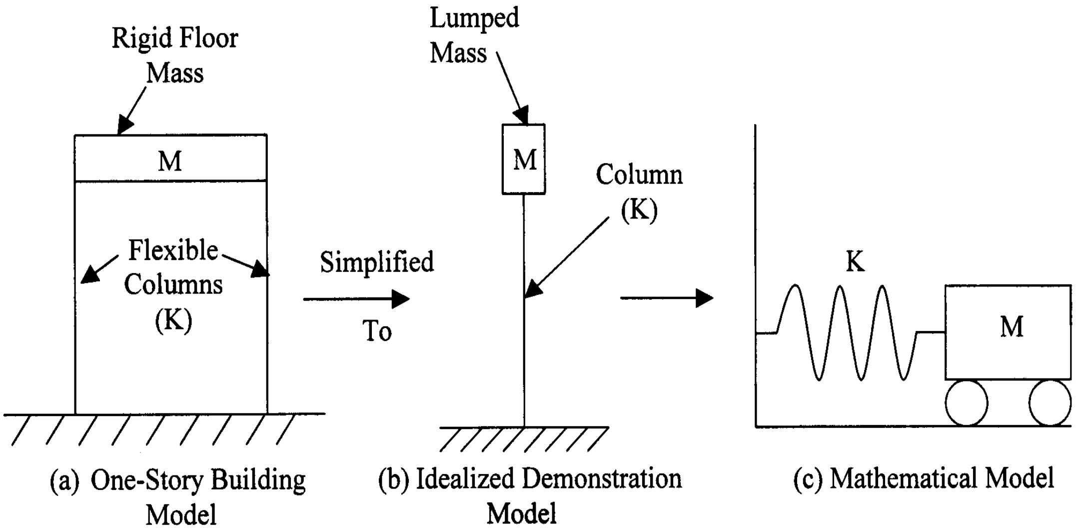


Figure 6. Idealization Models for a One-Story Building

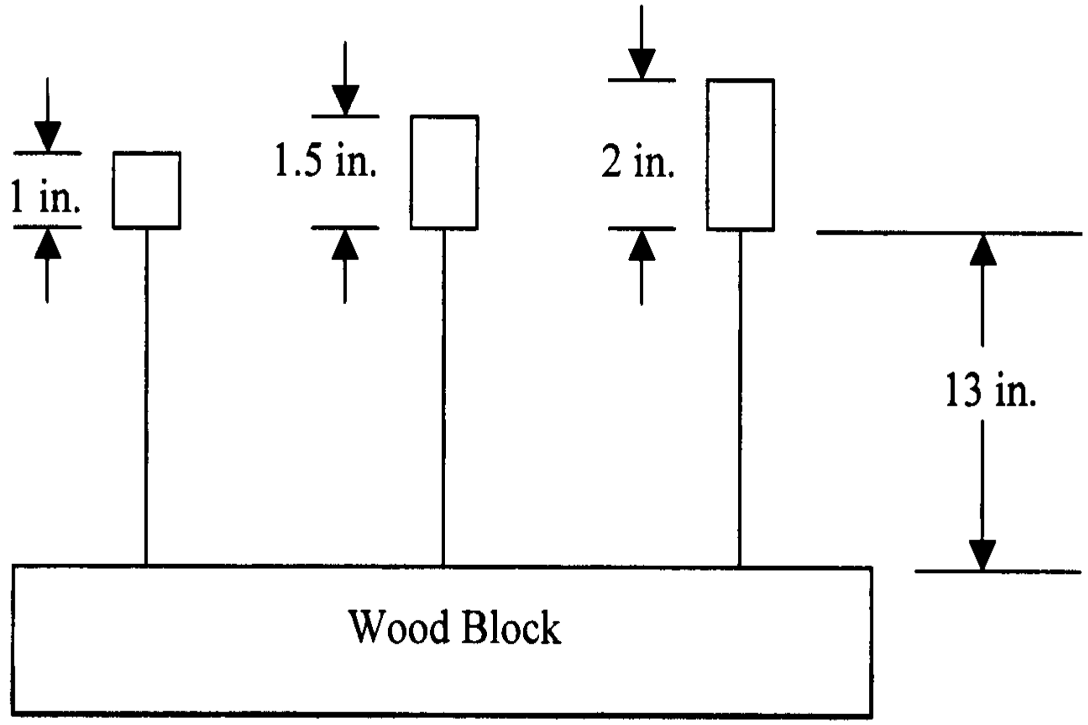


Figure 7. Lumped Mass Model to Demonstrate the Effect of Floor Mass on Natural Frequency

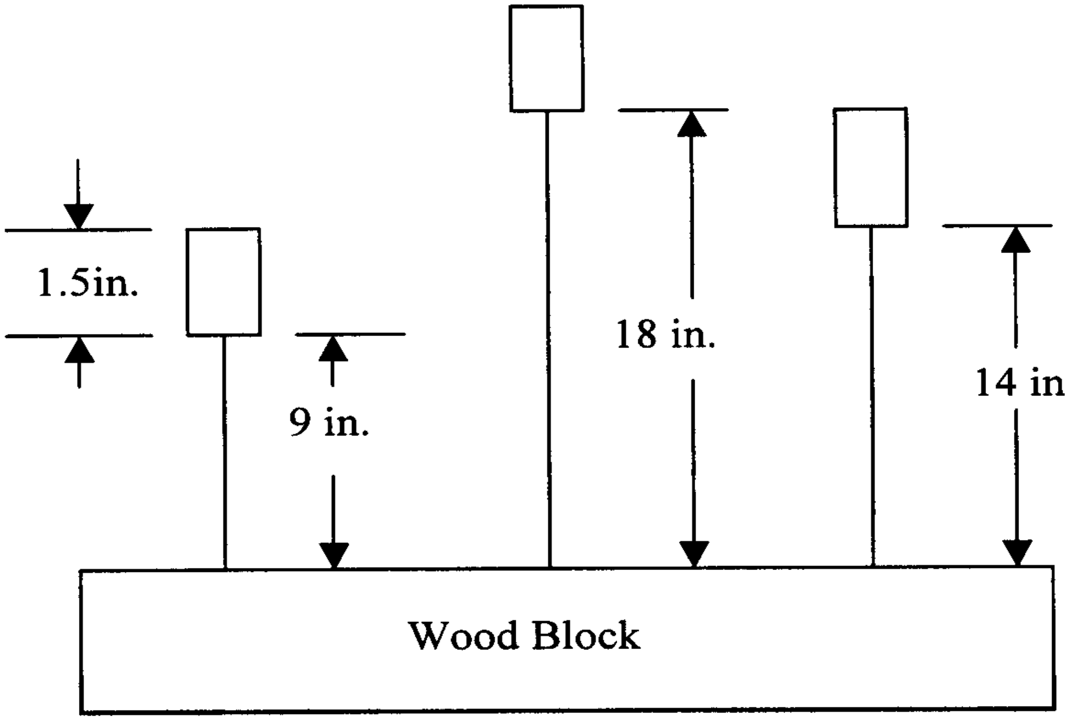


Figure 8. Lumped Mass Model to Demonstrate the Effect of Story Height or Column Stiffness on Natural Frequency

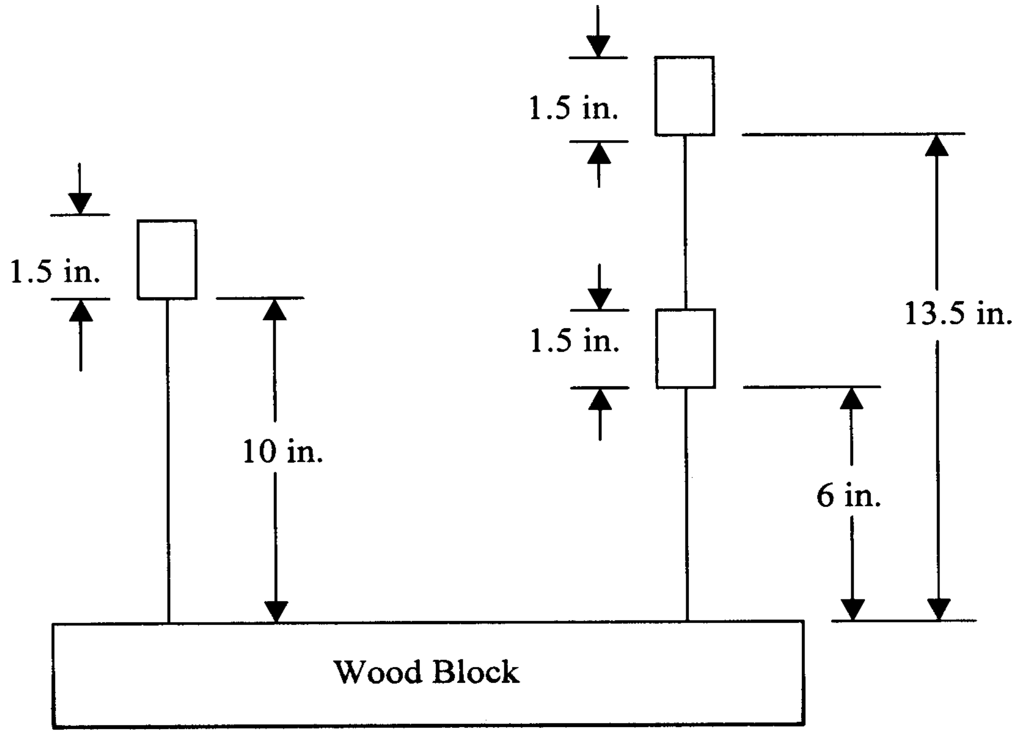


Figure 9. Lumped Mass Model to Compare the One-Story and Two- Story Dynamic Performance

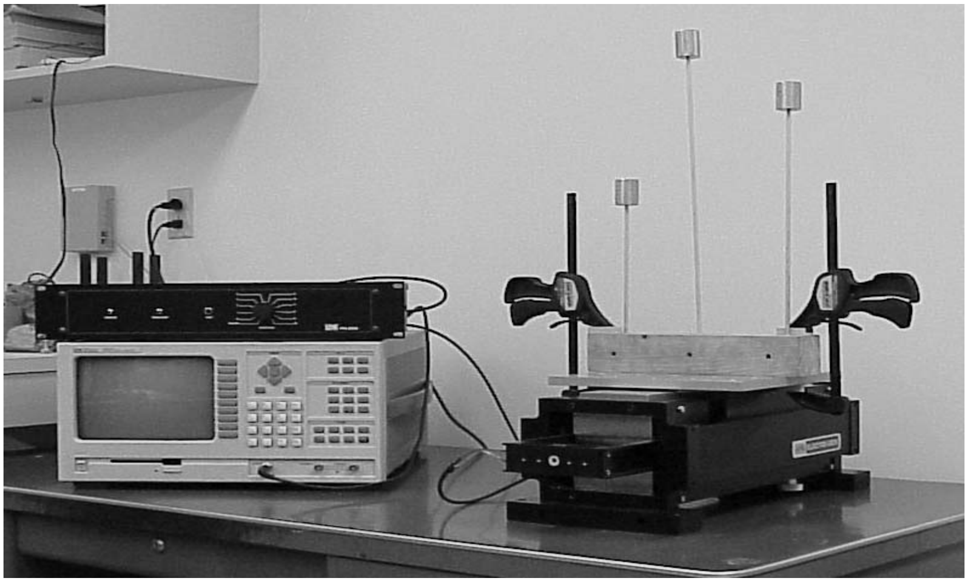


Figure 10. Photograph of Lumped Mass Model Apparatus to Demonstrate Effect of Base Motion Frequency on Different Stiffness Models

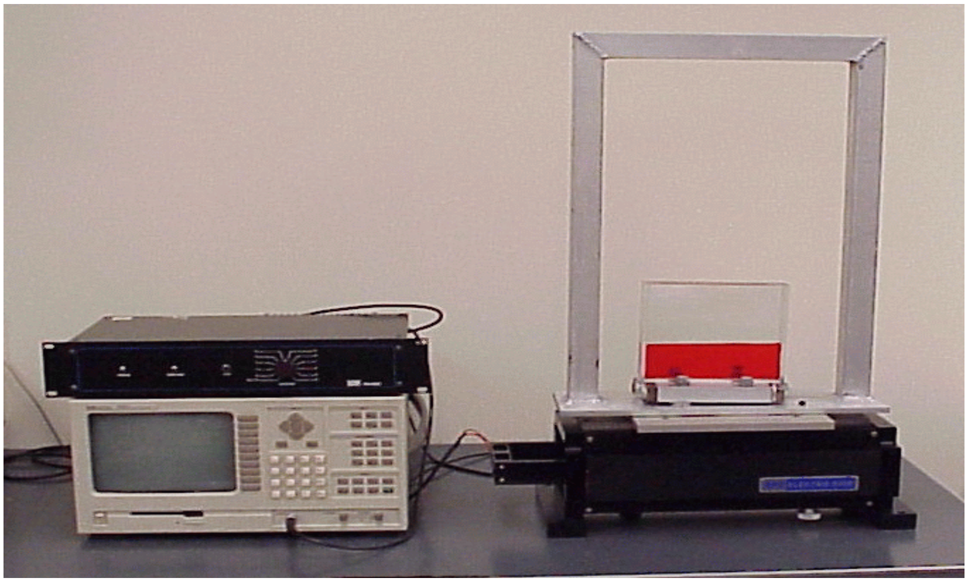
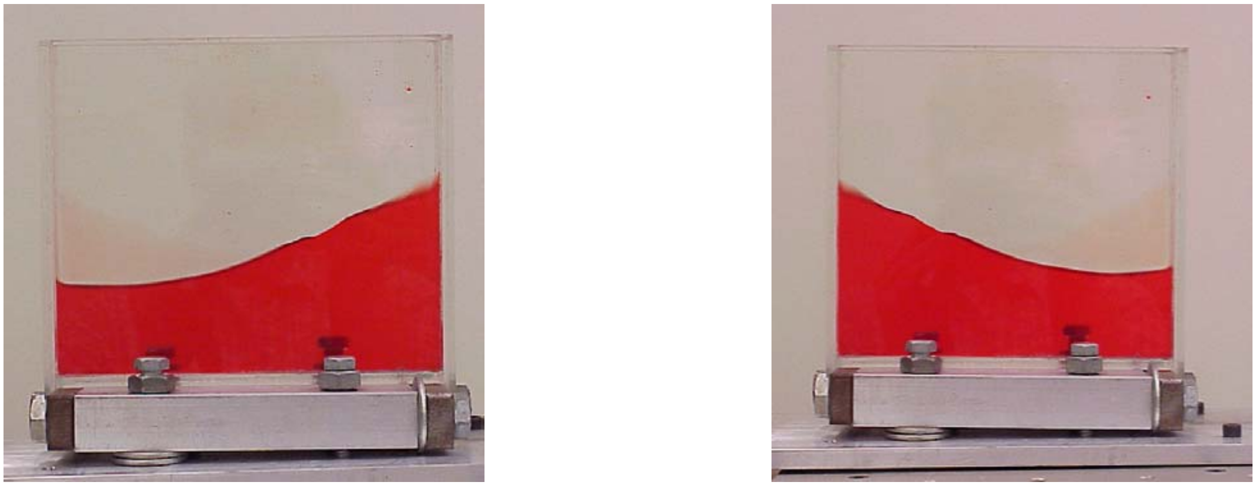
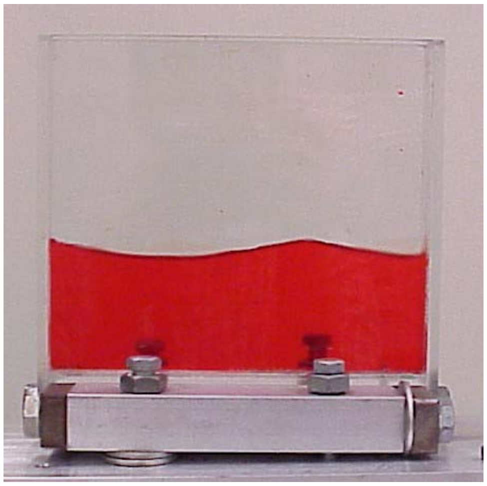


Figure 11. Photograph of Water Tank Model Apparatus to Demonstrate Ground Motion Profile During an Earthquake



(a) Profile at Two Hertz Ground Motion



(a) Profile at Four Hertz Ground Motion

Figure 12. Photographs of Profiles Generated From the Water Tank Model

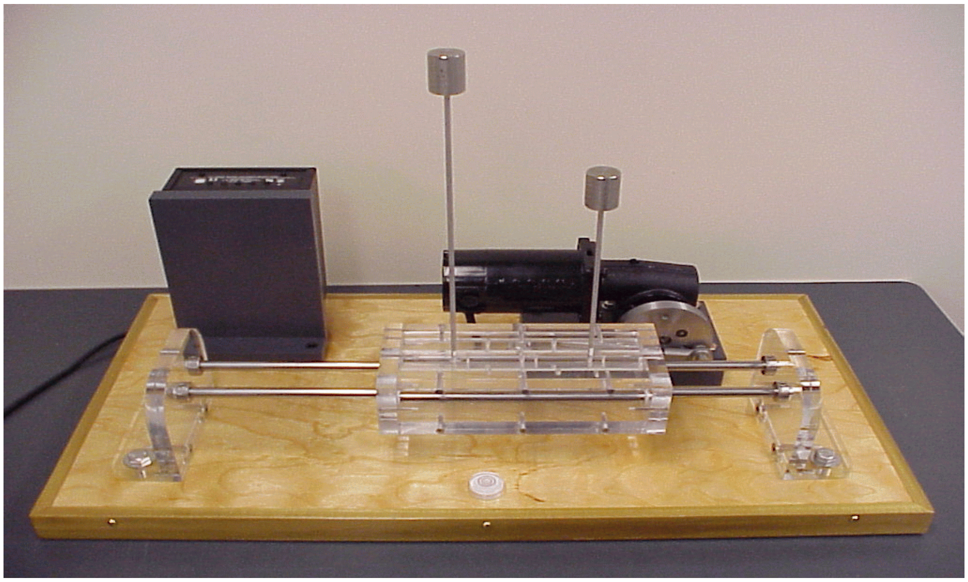


Figure 13. Photograph of the Model Shake Table with Lumped Mass Models Mounted on it