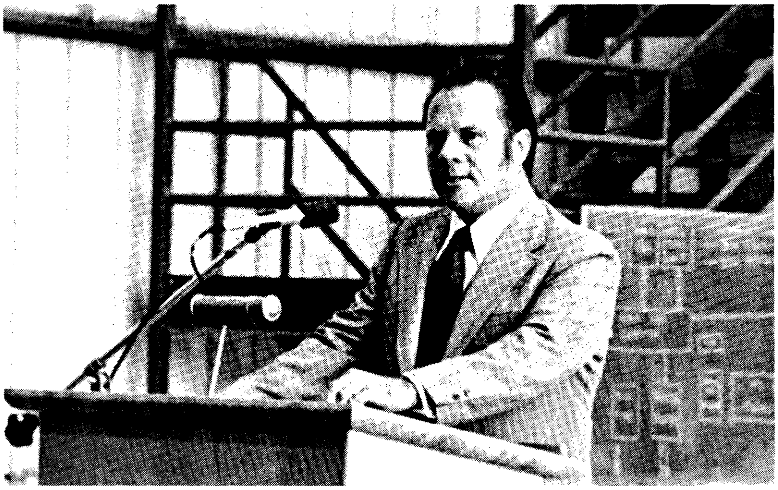
DEDICATION

Earthquake Simulator Laboratory

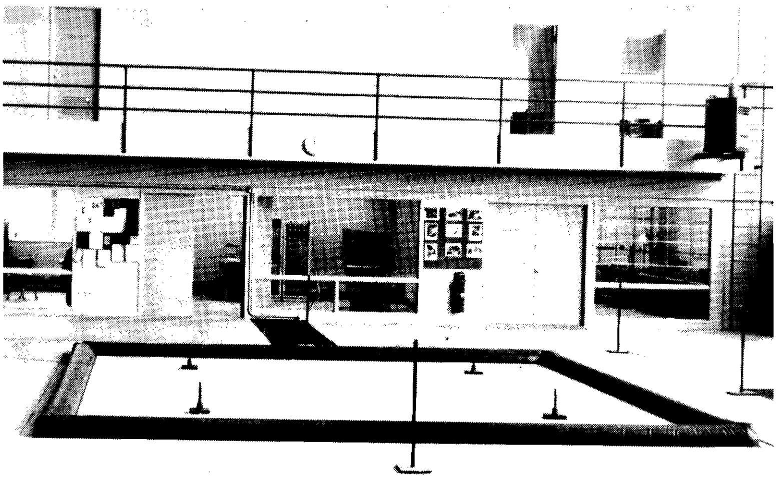
1972

ACKNOWLEDGEMENT

The Earthquake Simulator Laboratory was constructed through a series of grants from the National Science Foundation. This support is hereby acknowledged with sincere appreciation.



J. Penzien



Shaking Table and Control Room

Welcome

J. PENZIEN

Director of
Earthquake Engineering Research Center
University of California, Berkeley

It is my pleasure to welcome all of you here to participate in the dedication of this new facility—the Earthquake Simulator Laboratory. The central feature of this laboratory is the shaking table upon which I am now standing. It is hydraulically powered, electronically controlled, and is capable of producing motions that simulate the surface ground motions resulting from major earthquakes. The table can support test structures weighing up to 120,000 pounds and having heights as great as 40 feet.

Clearly, this unique facility greatly expands our experimental research capability. We will now be able to study the dynamic response and failure characteristics of large-scale structural components and systems under realistic conditions. The knowledge gained in the process will assist in improving seismic resistant designs.

With this objective in mind, it is indeed fitting that a large and representative group of practicing engineers are present here today. For you will eventually become the recipients of our findings, not only from the research to be carried out in this laborotory but from the entire theoretical and experimental research effort of the Earthquake Engineering Research Center. I am confident such information will greatly aid in your continuing effort to improve building codes and to advance the practice of engineering.

To be effective in this overall effort, however, it is important that we further improve the channels of communication in both directions between our research staff and the practicing profession. As one step in this direction, I should like to announce the appointment of an Advisory Committee to our Center made up of practicing engineers. The following individuals have accepted membership on the committee:

1. John A. Blume, President
   John A. Blume & Associates, S.F.
2. Walter A. Brugger, Chief
   Engineering Research and Development Bureau
   Department of Building and Safety, L.A.
3. Henry J. Degenkolb, President
   H. J. Degenkolb and Associates
   Consulting Engineers, S.F.
4. Stephen E. Johnston, Chief Structural Engineer
   Skidmore Owings and Merrill, S.F.
5. C. W. Pinkham, President
   S. B. Barnes and Associates, L.A.
6. Stanley D. Wilson, Senior Vice-President
   Shannon and Wilson, Seattle

Dr. Blume has agreed to serve as the committee's chairman.

Through this committee, I welcome your views and comments on all matters pertaining to earthquake engineering research, for we share a common goal, which is to minimize loss of life and property damage during future earthquakes.

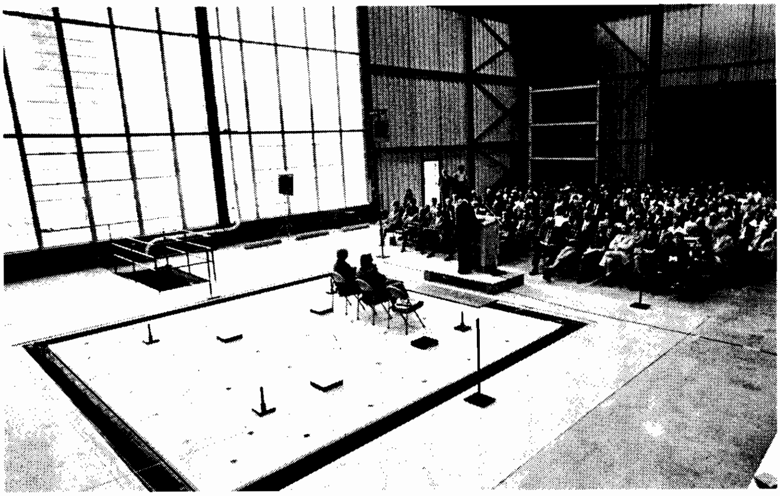
DEDICATION OF EARTHQUAKE SIMULATOR LABORATORY

June 24, 1972

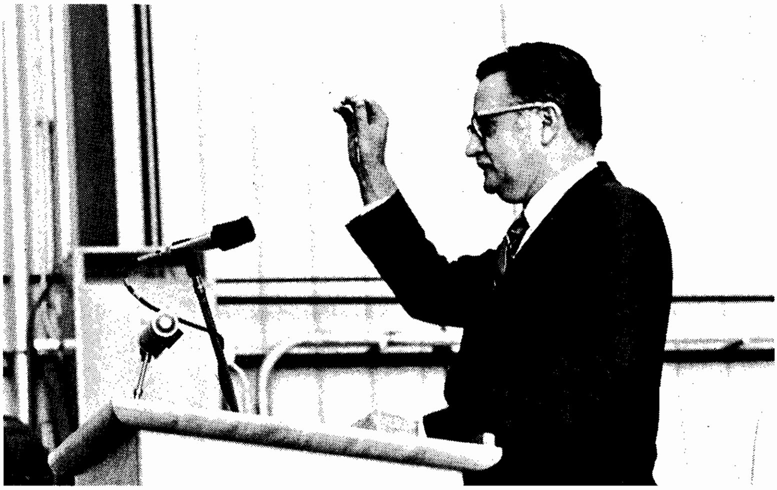
EARTHQUAKE ENGINEERING RESEARCH CENTER

COLLEGE OF ENGINEERING
UNIVERSITY OF CALIFORNIA, BERKELEY

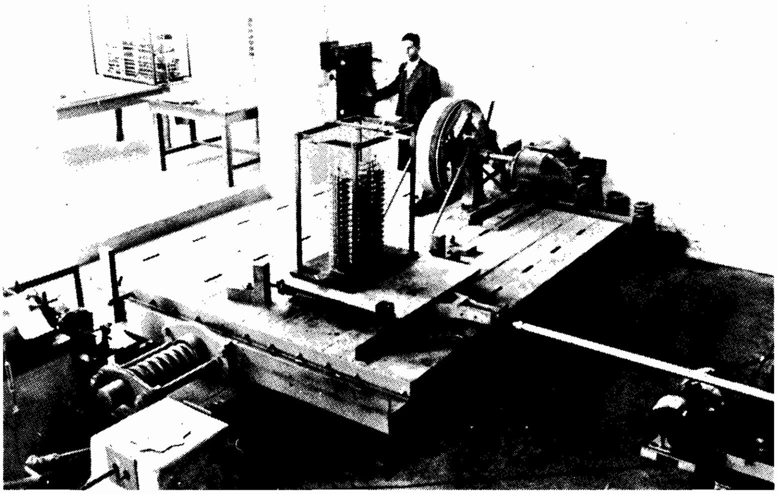
Contents



Dedication Ceremony
June 24, 1972



John A. Blume



View of a 16-Story Model on the Stanford Shaking Table. The Model is Mounted on a Cross Motion Platform

Early Research in the Dynamic Aspects of Earthquake Engineering

JOHN A. BLUME

President, John A. Blume & Associates Engineers · San Francisco, California

INTRODUCTION

Earthquake engineering and structural dynamics are active and popular subjects today not only at the academic level but in much design activity, in building codes, in government regulation of nuclear and other plants, and in legislative and technical committees at local, state, and national levels. It was not always like this. Funds for research were meager and sporadic, if indeed they were available at all for more than a year or two after each major destructive earthquake. The digital computer did not exist nor did the many electronic instruments and devices so useful today. In spite of these deficiencies and lack of public interest and support, research was conducted and much of it was ingenious and highly productive.

This is an informal history of pioneering efforts in shaking table research, in free vibration, in forced vibration, in determining the dynamic characteristics of real buildings, and in modeling and analysis techniques—all prior to the advent of the digital computer and sophisticated electronic devices.

The intention is to cover the major earthquake engineering and structural-dynamic research efforts applied to the earthquake problem. However, as in all histories, some worthy cases may be omitted, especially some in other countries than the United States about which the writer may have less literature and personal knowledge. Any such omissions are entirely inadvertent and regrettable. The purposes of this paper are the same as for any history—to clarify the record, to show new workers in the field what their predecessors did or attempted, hopefully to inspire and to stimulate new or extended efforts, to avoid old pitfalls, and for general knowledge. The emphasis is on experimentation and measurements, the reconciliation of theory and data, and on modeling and mathematical techniques related to the dynamic properties and responses of soils, water, structures, and building elements. Many used simple devices or models to illustrate free or forced vibration in a general way. These demonstrations are not considered as "research" efforts herein unless the models were made to scale and reliable measurements were taken in controlled experiments. Damage investigations, although important, are not considered as dynamic research for the purposes of this review, nor are static or slow loading tests or static analysis procedures which neglect the element of time.

It will perhaps be helpful first to consider the background and the climate in which the early efforts were undertaken.

The history of research and experimentation in earthquake engineering and dynamics applied to same clearly shows that each major destructive earthquake starting in 1906 led to some research that was valuable but of limited duration. The funds were sparse and subject to erosion as memory of the earthquake damage grew more vague with time and was replaced by concern over other problems. This was most unfortunate in that earthquake engineering progress was slowed, or stopped, while buildings and other structures of less than ideal seismic resistance continued to be created. Fortunately, a few investigators did some continuing work without funds in their spare time and at their own expense. The record shows some research activity following San Francisco 1906, the Tokyo area 1923, Santa Barbara 1925, Long Beach 1933, and Kern County 1952. Of course the major research stimulators came in the later, computer-era years, with the champion of them all no doubt to be the 1971 San Fernando earthquake.

There were no strong motion earthquake records until 1933. The few there were from that time to the computer era were not all good records although the ones that could be used were indeed welcomed, sometimes as though they represented all earthquakes to come. The response spectrum was developed from a mechanical experiment in the early 40's and thus was not available in prior years. Instead, there was much speculation about "dominant" and "dangerous periods" of ground motion.

What the research workers lacked in modern equipment they made up for in enthusiasm and dedication. They also had low labor rates, such as 50 to 75 cents per hour for the selected few with special aptitude and advanced degrees. A basic problem was the essential lack of a multi-disciplined approach. Communication was not always effective between seismologists, geologists, research workers in dynamics, structural engineers, and architects. Those few who engaged in shaking table work and the making of dynamic models of buildings generally had training—not in structural engineering—but in physics or mechanical engineering. They had little understanding of what they considered the sometimes rather gross assumptions and procedures of the designing structural engineer. Conversely, the structural engineers, with perhaps one or two exceptions, had little real understanding of the researchers' problems, needs, or language. The writer sensed the need 40 years ago and decided then to combine structural engineering and dynamics. Courses were taken outside the structural curriculum and dynamics became a passion. Buildings were treated not as fixed structures but as moving things with interesting dynamic characteristics in a new world where time and energy had to be considered as well as forces. The problem was the sparsity of earthquakes and of earthquake records and—of course—of funds for such "nonsense." The solution was to work in structural dynamics to the extent possible for compensation, and to work in it as a hobby when necessary living expenses had to be earned in some other type of work. The writer is pleased that things have improved today to the point where a structural-dynamicist is not only considered a rational person but his services are in demand, and for compensation!

SHAKING TABLES

1. Shaking Tables at Stanford University

A shaking table was used for experiments on the dynamic response of soil to ground motion as early as 1906, at Stanford University. This pioneering effort by F. J. Rogers, apparently then an assistant professor of physics, is well documented in the Report of the State Earthquake Investigation Commission on the April 18, 1906 earthquake.[(1),(2)] The work, which was suggested by Stanford's Dr. J. C. Branner,

> "——was undertaken with the hope of offering some explanation, based directly on experiment, of the greater destructiveness of earthquakes in regions where the foundations of structures are supported by more or less soft ground than where these foundations are based on solid rock."

The Mechanical Engineering Department at Stanford constructed the shaking table after what was no doubt a soul-searching design phase as evidenced by the following quotation from the report by Rogers:

> "In designing a shaking apparatus to imitate an earthquake, certain conflicting conditions must be taken into consideration. It would seem that the apparatus ought to be on as large a scale as possible, but if it is on a large scale, it must needs be very expensive. If the linear dimensions are increased in any ratio, say trebled, the volume, weight, strength, and power to operate must be increased in the cube of this ratio; hence if the linear dimensions are trebled, these quantities must be increased 27-fold. Moreover, it is obviously impossible, at any cost, even to approach the scale on which nature acts. With these considerations in view it was decided that the scale of the apparatus should be as small as is consistent with obtaining results from which general conclusions might be drawn."

The device consisted of a box called a "car" 100 × 86 × 30 cm deep on steel rollers 4 cm in diameter. The rollers and the drive mechanism were on a heavy timber framework, well bolted together. A direct current motor drove a 75 kg balancing wheel which in turn drove a connecting rod between the car and a crank connected eccentrically to the hub of the wheel. The adjustable eccentric allowed car motion up to 10 cm. A recording drum on independent supports made pen-on-paper records of time, the car motion, and the motion of a block set in the upper portion of the sand in the car. The recording drum was simply rotated by hand but the second ticks provided the vital time data.

The tests were made with construction sand 22 cm deep under various moisture contents: "moderately dry" (water $<$ 10% of total weight) to "almost fluid" (water 20% of total weight). The frequency range for the table was made from 0.5 to 4.6 cps. Altogether, 74 tests were made with table frequency and amplitude, and sand moisture content as the principal parameters.

It was found that the moderately dry sand moved as the car at frequencies less than 2.5 cps, but that wet sand had much more motion than the car. The wet sand lagged the car's motion about 1/6 of the period and had almost uniform velocity until reversing direction with severe accelerations. The tests also included layers of material with different characteristics and moisture content. Rogers concluded:

> "To those interested in seismology the important question is: How do these experiments help to explain the greater destructiveness of earthquakes in regions where foundations are in alluvial soil than where foundations rest directly upon rocky strata? To pass from experiments upon a box containing half a ton of soil to the destructive effects of an earthquake is certainly a great leap. In taking such a step, one is very likely to make mistakes. However, it seems to me beyond question that a soft, semi-fluid mass of soil, containing a large amount of water and surrounded or partially surrounded by soil strata, will not oscillate with the same motion as the surrounding strata. Moreover, in the case of the frequencies ordinarily occurring in earthquake motion, the amplitude of the oscillation of such a semi-fluid mass is likely to be greater than that of the surrounding solid strata; also the reversal of motion or the acceleration during reversal is likely to be greater than in the case

> of solid strata. Finally, the greater relative motion of such a soft or semi-fluid mass is not prevented by overlying strata of drier and more compact material."

Elsewhere in the same report[3]* Harry Fielding Reid develops theory for the Rogers' experiment including the natural period of the sand layer as a "soil column." He notes in closing:

> "It is clear from Mr. Rogers' experiments that the forces when the sand is dry are very different from those when the sand is very wet; and when different parts of the sand contain different amounts of water, that the movements would be so different as to produce much confusion."

The Santa Barbara earthquake of 1925 brought renewed interest in earthquake engineering research, especially since this was only two years after the tremendous loss of life in Japan. Dr. Bailey Willis of Stanford proposed that the Stanford School of Engineering develop a vibration laboratory consisting mainly of a shaking table. An anonymous gift in 1926 made this possible. The table was designed by Dr. Lydik S. Jacobsen in late 1926, and during 1927 and 1928 it was built and first put into use.

The platform was made of 8-inch steel H-beams bolted and welded together; it was 10 ft by 12 ft and weighed about 6000 pounds. It was carried on specially ground streetcar

* A footnote in this same report obviously refers to the now popular theory of continental drift: "Mr. Bailey Willis, on account of the forms of the mountain ranges bordering the Pacific Ocean, has concluded that the bed of the ocean is spreading and crowding against the land. He thinks in particular that there is a general sub-surface flow towards the north which would produce strains and earthquakes along the western coast of North America. Science, 1908."

wheels mounted on ball bearings. These car wheels ran on two rails. Concrete abutments fixed in the floor received the thrust of large horizontal springs situated between the platform and the abutments. The springs were changeable, so as to vary the "ground" frequency.

The platform was actuated by two independent means, impact of a half-ton pendulum, or by a rotating unbalanced flywheel driven by an electric motor. With the pendulum there would be a short contact time followed by free vibration of the table. With the motor drive there would be continuous forced vibration, steady state.

The dynamic characteristics of the table, the pendulum-table system, and the forced vibration were all developed in detail together with the complete theory.[4] There were many possible adjustments to create a wide array of disturbances, frequencies, accelerations, etc.

Recording devices varied with the model being tested. For non-destructible dynamic building models with exaggerated story distortions, moving pictures were taken of the whole model which had levered dials showing the relative distortion of adjacent stories. The absolute distortion relative to "ground" was also recorded.

Following are some of the experiments conducted on this shaking table.

A. Dynamic Behavior of Models of Timber Walls[5]

This investigation by Lydik S. Jacobsen was on the relative merits of diagonal and horizontal sheathing under dynamic loading. Wall panels nine feet square made of 2 × 4 studs with 1 × 6 sheathing were placed upright on the shaking table, guyed, loaded to simulate building conditions, and force vibrated. In addition, models were made to scales of ¾, ½, ⅜, and ¼ of the full size panel to evaluate dynamic scale effects. Reference 5 gives the complete results.

B. Motion of a Soil Subjected to a Simple Harmonic Ground Motion[6]

This work by Jacobson was started in the summer of 1928. A strong wooden box 2½ × 3½ × 16 feet was constructed and secured to the shaking table. The unbalanced flywheel was used to drive the table. All soil tests were made with a Monterey sand. Moisture content was varied as was the length of the box, the depth of sand, and the frequency and amplitude of the motion. The tests clarified certain points regarding the Rogers' experiments and the Reid theory on the Rogers' experimental results, and also provided considerable new information. Reference 6 provides all data and a comprehensive discussion.

C. Water Pressure in a Tank Caused by a Simulated Earthquake[7]

In this series of tests by Leander M. Hoskins and Lydik S. Jacobsen, a tank 8 feet long by 18 inches wide and 24 inches high used alternatively with two equal compartments or one compartment was placed on rollers on top of the shaking table. The tank was connected to the table at one end through a dynamometer with stiffnesses of either 10,500 lb/in, 6400 lb/in or 2200 lb/in. Water depths tested were 6, 9, 12, 15 and 18 inches. The shaking table periods used were nominal ¼ sec, ½ sec and 1 sec. The pendulum bumper was used to excite vibration. The work was mainly done in 1932. Recordings were made by various means including motion pictures of open ended glass standpipes with ink-colored water. Comprehensive data were taken and compared to theory as developed by Westergaard. The effective mass of the water is given for various conditions. Theory and experimental data checked well.[7]

D. Dynamic Shear Model of a 17-Story Building Tower

In 1930 and 1931 Jacobsen constructed and tested a dynamic model of a proposed 17-story building tower on a large base portion of several stories. The model was a mechanical one with springs for the stiffness of the columns and walls and steel plates for the lumped masses of each floor. This model had no vertical freedom so it represented a shear-type distortion wherein the floors remained level. Experiments were conducted for both a conventional first story and one having considerable flexibility—the "flexible first story" concept. The model was placed on the shaking table which in turn was either force-vibrated, subjected to free vibration following pendulum impact, or given a chaotic motion. Motion pictures were taken to obtain the story distortions.

Although this was a comprehensive pioneering effort it was private work and was not published. The model is now in the writer's office for rehabilitation and preservation.

E. Dynamic Model of the Alexander Building, San Francisco

This dynamic model was based upon data derived in detail by reconciling the computed natural periods of vibration of an existing 15-story building with the measured natural periods[8] in a comprehensive thesis program by Blume and Hesselmeyer.[9],[10] The building was found to have a significant amount of flexural freedom as well as some foundation (soil) freedom so the model was made accordingly. This meant the design of a mechanical model with 5 or 6 degrees of freedom per story. Scale considerations and similitude conditions ruled against 6 degrees of freedom, so 5 were elected. They were obtained with horizontal coiled springs for horizontal story translation and twist, and vertical "springs" consisting of calibrated thin gauge plates spanning aluminum cylinders and supporting each floor above on ball bearings riding on the plates. These bearings permitted biaxial horizontal translational motion. Vertical translation at the center of mass was prevented by cantilever supporting arms. The original model was designed by Jacobsen and Blume and was built by Blume in 1934. After considerable testing, resulting in modification of recording devices, and participated in by two graduate students, E. P. Hollis and R. S. Ayre, tests on the shaking table were completed in March 1937.[11]

The length scale of the model was 1 to 50 and the mass scale 1 to 50^3. The stiffnesses allowed for shear, flexural and ground distortions. Experiments were conducted with various first story and soil stiffnesses. The details of the model, the procedures and the results are contained in reference 11.

This was an exotic model of a tall building which was the first (and only) 5-degree-of-freedom-per-story multistory building model of the lumped mass and spring type. It could be tested over and over without damage and its local characteristics could be altered for parameter studies. No doubt such models would have been continued and extended if the computer had not come along. There is still a great potential with a combination of mechanical, structural, or electrical models with the digital computer.

F. Additional Experiments

Additional experiments conducted in the Stanford Vibration Laboratory by Williams, Ayre and Jacobsen are described in references 12, 13, and 14.

2. Shaking Tables at Massachusetts Institute of Technology

A small but carefully planned and controlled shaking table was developed at Massachusetts Institute of Technology by

Arthur C. Ruge in the 1930's, then research associate in seismology who wrote an interesting paper on model scaling and similitude, reference 15. The first table, suspended by piano wires and actuated by springs, was driven by rotating equipment to produce essentially simple harmonic motion. A 1 to 46.5 scale structural model of an elevated water tank was tested to the elastic limit on this table.[(16),(17)] Such structures had suffered collapse and damage in the 1933 Long Beach earthquake and were of considerable interest.

Subsequently, in consultation with Vannevar Bush, then dean of engineering at M.I.T., Ruge developed a more exotic drive mechanism which duplicated the actual motion of recorded earthquakes. This was termed a "shadowgraph" or optical cam. An electric "eye" scanned the edges of a rotating cam cut out to match the actual earthquake record. The light beam in turn actuated a control valve mechanism for an oil pressure system which in turn caused the table to move in accordance with the earthquake cam.[(17),(18),(19)] A 1 to 25 scale structural model of an elevated water tank was tested using the strong motion record for Long Beach 1933. Valuable information was obtained regarding the response of elevated water tanks.

3. *Shaking Tables in Japan*

Although there are large shaking tables in Japan at this time the writer has no information on Japanese shaking table experimentation prior to 1936 and that work was on very small scale models of earth dams. It must be recognized that in the field of soil mechanics there has been considerable experimentation with vibration insofar as obtaining properties of soil samples is concerned. Such work on soil samples is not included in this paper which is limited to work with scale models of structures such as used in Japan.

At the Second Congress on Large Dams, Washington, D.C., 1936, Mononobe, Takata and Matumura reported on "Seismic Stability of the Earth Dam".[20] Included in their work was shaking table experimentation on two small models of earth dams. Periods and amplitudes were measured and the observed amplitudes compared favorably with calculated values.

4. Shaking Table Work at UC Berkeley

The first work at the University of California, Berkeley, with models on a shaking table was published in the proceedings of the Soil Mechanics and Foundation Division, ASCE, in April 1956. However, there must have been a considerable time lag between the work and the publication because the writer's files contain a typed report about the same work by Ray Clough and David Pirtz which report was received in October 1952.

The shaking table was a 7′ × 10′ reinforced concrete slab 8″ thick mounted on 4 steel plate legs, oriented so as to be quite flexible in the direction of motion. A 27″ high bin was constructed on top of the slab in which scale models of rockfill dams were built and tested. One end of the concrete platform was anchored by a heavy spring which provided frequency characteristics to the system and the other end was struck by a 150 lb. pendulum to induce the table motion.[21]

Crushed quartzite with a maximum size of ⅜″ was used for the rock and clay for the cores. The length scale of the models was 1:150. Direct writing recorders were used. This table has been used for much additional work by Seed and others.

BUILDING PERIOD MEASUREMENTS

Certainly a big step forward was associated with measured periods of vibration of buildings. Without reliable measurements no research can advance. Elmer E. Hall, Associate

Professor of Physics, University of California, Berkeley, pioneered in this work as early as 1912.[22] He noted that others in Japan had previously measured wind-induced building motion but no one had measured motion induced by traffic and other minor disturbances. Today such motion would be termed "ambient," now a popular word.

The instrument used was designed by Professor Hall. It was rather heavy and awkward to handle, but it had a wide range of adjustments for recording speed and sensitivity and it measured three components. Points wrote on glazed paper smoked with kerosene. Motion was recorded in six buildings in San Francisco, often for many hours at a time. In one case, the Ferry Tower, motion was continuously recorded for 48 hours. Even the effect of tides was considered.

The measurement of building periods was resumed in the United States in 1931, with the same Hall instrument, by Professor Perry Byerly, James Hester, and Kenneth Marshall of the University of California.[8] The then tallest buildings in San Francisco were measured, most of them constructed since Hall's original measurements. The results for 15 buildings together with descriptions are given in reference 8. One of the buildings, the Alexander Building, was selected two years later for intensive study[9],[10] in which the measured periods played an important role.

The measurement of wind-induced and ambient motions of buildings was undertaken on a broad scale by the then U. S. Coast and Geodetic Survey, as part of its 1934–1935 California earthquake investigation program. Improved portable instruments were used in hundreds of buildings and other structures. The records obtained were carefully scaled and reported[23],[24] and provide a most valuable fund of information. The work has continued, on a reduced scale, to this day.

In addition to wind-induced and ambient motion, special studies were also made in the USC&GS program on free vibration, especially of elevated water tank towers. The structures were simply pulled horizontally a safe distance and then suddenly released. Vibration measurements clearly showed the decaying free vibration versus time following the release. From such data it was possible to obtain natural sloshing and structure periods and damping ratios[23],[24] and to study beating phenomena. Those principally engaged in the field work of the early USC&GS program included Ulrich, Carder, McLean, Moore and Blume. The forced vibration part of the USC&GS program will be noted subsequently.

ANALYSIS PROCEDURES

1. The Alexander Building

Although the theory of vibration of prismatic bars was well known in 1933 (Bernoulli and Euler worked on this in the 18th century) and it was tempting to idealize a building as a vertical cantilever bar fixed at one end,[25],[26] essentially nothing was known of the properties of real buildings or of how to compute their natural periods of vibration from the drawings before they were constructed. There were many questions such as: how much of the freedom is due to shear distortion, to joint rotation, to overall flexure of the building, to soil tanslation and rocking; how do the various building elements, such as floor slabs, walls, filler walls, partitions, stairways, frame, etc., participate and interact; what is the effective modulus of elasticity or of rigidity of steel, concrete, masonry, etc., as combined in a real building; how do these values vary, if at all, from mode to mode; how does one compute the effective story stiffnesses and the various periods and mode shapes; etc.? Such information was needed not only for dynamic model design but as a means of understanding complex real buildings and of making progress in dynamic analyses in research or for design. This was a combined problem in structural engineering and dynamics, or "structural-dynamics."

A comprehensive study for reconciling calculated with observed periods was made in 1933 and part of 1934 by Blume and Hesselmeyer at Stanford University.[9],[10] The 15-story Alexander Building in San Francisco was selected because it was rectangular in plan and fairly symmetrical, four of its translational natural periods were known,[8] and it was free on three sides and had only a 4-story building adjoining on the fourth side. It had a steel frame, concrete floors, brick filler walls, and tile partitions—typical of the contemporary highrise buildings. The study's purpose was to provide data that would disclose the numerical values of some of the building's unknown properties. The work included not only detailed structural analysis but extensive iterations (then called "trial and error") to reconcile the computed periods with the measured.

No digital computers were available to help in the countless trial solutions for the four periods of the 16-mass system, but there was an electrically driven desk calculator (which had to be rebuilt because of wear when the work was over). Many new period calculation procedures were developed as part of the study. To my knowledge it was the first detailed treatment of a real multistory building as a lumped mass system.

The same building was subsequently studied as a model on the shaking table[11] as previously noted, the actual building was tested in extensive forced vibration,[27],[28] and by further analysis.[10] It has no doubt become the world's most studied building, an earthquake guinea pig, and it has produced valuable data on building properties and analysis procedures.

2. Box Cantilever

Based in part upon data from the Alexander Building studies, Jacobsen wrote a comprehensive paper on buildings as idealized hollow box cantilevers.[29] The work considered various degrees of freedom and means of applying theory of prismatic bars to building problems where the walls are massive compared to the frame and tend to dominate the stiffnesses and therefore the building characteristics.

3. Integration and the Response Spectrum

The problems of integrating strong motion records and the related one of computing the responses of simple elastic oscillators to such records were at hand after the USC&GS obtained the initial strong motion records in 1933. Several considered this in various ways—by means mathematical, graphical, mechanical and electrical—including Neumann,[30] Benioff,[31] Biot,[32] Ruge, Jacobsen, Martel, Housner,[33] White,[34] and Glover. Theory alone was not enough because of the tremendous amount of labor required. The torsional mechanical analyzer was considered by Neumann[30] and one was developed by Biot together with actual earthquake spectra,[32] the concept for which had been seen by Benioff.[31] One must admit that man was finding useful methods even before the digital computer.

4. Phase-Plane Delta Method

A graphical step-by-step method of response analysis that was general and powerful even for the transient stage of damped non-linear systems under random disturbances was Jacobsen's phase-plane delta method.[35],[36] The advent of the high-speed digital computer decreased the need for this method, but it too was available.

5. *Characteristics of the Ground*

Much work in the characteristics of the ground, in the characteristics of soil layers, and in the propagation of seismic waves has been done in Japan. Earthquake and microtremor motion has been measured underground and on rock and theory of dynamic soil analysis has been advanced. Kanai, Takahasi and Kawasumi reported on this in 1956[61] but much prior work had been done by Kanai and others.[62],[63],[64] This material is supplemented today by more recent analysis procedures for the soil including elastic half space springs, shear column, lumped masses, finite element analyses, etc., which are most useful with modern computers.

6. *Inelastic Analysis*

A basic concept and procedure which also preceded the computer era is that of inelastic response, ductility and reserve energy capacity. The reconciliation of kinetic energy demand with the capacity to do work in the inelastic range was treated by Tanabashi[65] and was applied by Housner to a simple elastoplastic system.[37] Blume developed an inelastic analysis procedure for complex building systems with consideration of deterioration under cycling, period changes, the use of all available elements and materials, and multistory performance — in terms familiar to the structural designer.[38],[39],[40],[60] The Blume method termed the Reserve Energy Technique, under development for many years, seems to indicate in simple terms why complex structures behave as they do in severe earthquakes.

7. *Early Computer-Era Developments*

Although the time scope of this paper generally stops short of electric analog or computer-era developments, there was some overlap of hand and computer methods and it is desirable to at least note some of the milestones in the early days of electric analog or digital computer seismic operations. The work done for the Office of Naval Research by Alford, Housner and Martel on spectrum analyses is noted[41]; the work by Robinson in early spectral response computations related to the 1952 San Francisco joint committee code work on base shear and inverted triangular loading[66]; of Murphy, Bycroft and Harrison on electric analog techniques[67]; the work on modal combinations by Clough[42]; multistory response analysis by Blume in conjunction with Murphy using electric analog techniques[38]; of Tung and Newmark on digital analysis of shear buildings under earthquake excitation [68]; of Rosenblueth on probabilistic aspects[60]; the work by Penzien on inelastic response spectra[59]; and the work by Clough, Wilson and King on advanced digital computer analysis of complex multistory buildings.[43]

FORCED VIBRATION OF STRUCTURES

Vibrating machines of various types can be used to excite the dynamic response of buildings, bridges, dams, and the ground per se. They have also been used to vibrate specific parts or members of structures or machinery. The objective of such work is to determine natural periods and mode shapes of real buildings and to obtain values for damping. Some forced vibration was done in Germany in the late 1920's and in the 1930's where machines had been used to test railway bridges, to compact filled soil, and to determine dominant site periods. Work in buildings, however, was apparently limited to trial experiments with eccentrically weighted bicycle wheels in small frame houses. However, the basic theory of forced vibration with oscillators and resonant response was well understood.[25],[26],[44],[45],[46] The first attempt at forced vibration of large buildings or dams for earthquake engineering and structural-dynamic re-research was in the United States, as part of the USC&GS 1934–1935 California Seismological Program that followed the 1933 Long Beach earthquake.

A machine which would be portable, produce only horizontal or vertical harmonic forces as desired, and which would operate up to 600 RPM was designed by Jacobsen and Blume in the summer of 1934. Blume then built the machine in the Stanford University machine shops in the autumn of 1934 and subsequently conducted forced vibration experiments for USC&GS through 1935. Dr. Jacobsen was advisor in the program. Although the machine itself was an experiment, it successfully vibrated every structure in which it was used including the 25-story Los Angeles City Hall, large concrete dams, bridges, low rigid buildings, and even the ground. Various reports were issued on the results,[47] and the machine and the data have also been covered in the literature.[48],[49],[50],[51],[52],[53] The machine has been retired for possible metal fatigue after millions of cycles.

The second vibrator built in the United States for forced vibration was also made for the USC&GS. This was designed by Jacobsen especially for testing low buildings and it was constructed at Stanford University in the late 1930's. It only weighed 150 lbs. and it was small enough to fit within a doorway. It had high speed capacity, topping out at 960 RPM.[52]

The third vibrator was the heaviest and most powerful of the USC&GS machines. It was designed for USC&GS under a Navy contract by William D. Patterson. It followed the general Jacobsen/Blume concept of three wheels with opposing eccentric masses. This machine weighed about 500 lbs. and was intended for massive work including ground shaking.[52] One project in which this machine was used has been described in the Bulletin of the Seismological Society of America.[54]

The U. S. Bureau of Mines used a small machine to vibrate a four-story stucco building. The machine is described as having an electric motor with an unbalanced pulley, maximum speed of 1800 RPM and a maximum force of 90 lbs. Although the purpose of this experiment was to determine the natural frequencies of house elements and vibration problems in houses, the work is of interest.[55]

It is not entirely clear when the Japanese started forced vibration research but it is known that they first operated a small machine and later built a large machine but one that was not uni-directional in force application, in the early 1950's. The available literature has a paper by Kanai and Tanaka in 1951[56] and one by Hisada and Nagakawa in 1952.[57]

IN RETROSPECT

It is clear that until the 1933 Long Beach earthquake caused an increase in concern as well as a release of significant research funds and some needed legislative measures, progress was slow. Earthquake-resistant design was basically static, in more ways than one, even though classical theory on prismatic bars and on forced vibration was well advanced. Rigid-body or coefficient design ($F = Ma = CW$) was done in some cases especially in Japan, and in a very few cases some degree of resonant amplification, generally of prismatic bar cantilevers under harmonic motion, was considered. By intuition, and in part based on the early shaking table work at Stanford, the so-called flexible first story concept (which is again being considered) was a popular subject for debate. L. H. Nishkian employed this concept as early as 1927 but not in dynamic design per se.[58]

Ground motion was considered to have "dangerous period bands" and was in a very few cases taken in design as harmonic motion of either a few cycles or in steady state motion near resonant frequencies.

Outside of Rogers in 1906, Hall in 1912, Jacobsen in the late twenties and Byerly, Hester, and Marshall in 1931, this story did not begin until 1933 insofar as dynamic earthquake research is concerned. None of these men were structural engineers—they were physicists or seismologists with the exception of Jacobsen who was also in mechanical engineering. However, starting with 1933, work progressed on four basic fronts; shaking table models and research, extensive observations of building periods, forced vibration, and the detailed analysis of buildings, soil, and of strong motion records. The writer is grateful to have had the opportunity to work in all four areas, to be the first structural engineer to do so, and to have worked extensively with Dr. Jacobsen, a dedicated pioneer in the field.

It should be noted that several others—mostly scientists or structural engineers—although not participating in the actual research, had interest in it and provided encouragement for the work. These names would include Branner, Reid, Willis, Byerly, Hoover, Hoskins, Dewell, Huber, Galloway, Hammill, L. H. Nishkian, Heck, Chew, Freeman, Millikan, Day, Creskoff, Benioff, Derrick, Leonard, Bush, Gutenberg, Neumann, Martel, Richter, Suyehiro, Weed, Wood and others.

CONCLUSION

This review of early research in the dynamic aspects of earthquake engineering has generally stopped short of the extensive achievements brought about with the aid of the high-speed digital computer. The reason is that the computer is such a valuable tool for this field of effort that it has opened up a new world—one too lengthy to include herein. It is clear, however, that even without the computer, without other exotic electronic devices, and often without adequate funds, man was making progress—with shaking tables, models, machines for forced vibration, large but effective instruments, ingenuity, hard work, an understanding of classical theory, and intuition. There seems to be no reason why these tools and methods can not be combined with contemporary computers and equipment to make further progress much faster in the future.

There can be little doubt that the final solution of the technical aspects of the earthquake problem lies not alone in one discipline but in the proper application and coordination of many disciplines including seismology, geology, soil and rock mechanics, soil dynamics, architecture, structural engineering, mechanics, mathematics including statistical and probabilistic aspects, and of course structural-dynamics. If and when it becomes possible to reliably predict the exact time and place of major earthquakes, the problem will still not be solved unless the buildings and structures are truly earthquake resistant—people can not return to devastated cities. If the structures are made earthquake resistant, then the wisdom of costly evacuation—based on prediction—with the many problems could be questioned. Thus it would seem that structural-dynamics, or more accurately soil-structure-system dynamics, in all of its aspects, is a vital part of the earthquake picture of the past, the present, and the future.

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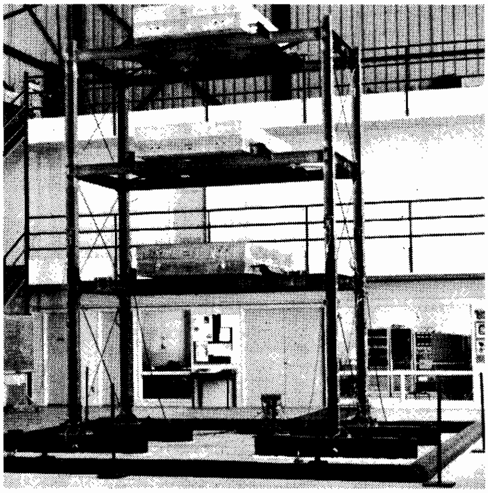

Shaking Table With Test Structure

On the Advancement of Research and Education in Earthquake Engineering

LOY L. SAMMET
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A new enterprise rarely is launched under circumstances so fully propitious as attend the dedication of this new laboratory in earthquake engineering. Let us note the following:

In the earth's seismic activity we have a physical phenomenon of worldwide scientific concern. Its practical aspects rise geometrically with growth in population and with increasing concentration of that population in large urban centers—often in areas of known seismic activity. Moreover, accelerating expansion in technology and the accompanying rise in the magnitude and complexity of engineering works compound the earthquake risk to human welfare and to capital investment, both public and private. For us here today, there is the special concern that we dwell in a region in which all these factors are present in urgent degree.

In the broadest sense, the University offers in this situation a long-established commitment to teaching, research, and public service. Specific to seismic phenomena and their scientific study, this commitment was expressed early in the establishment in 1887 of seismic recording stations on the Berkeley campus and at the Mount Hamilton Observatory, the first such stations in this country. From this beginning, and an expanded system of stations, has come an impressive flow of scientific work and student instruction and research. Along with this scholarly output, there has been a continuing and invaluable service to the scientific and public communities through immediately release of information concerning major seismic activity and through the regular, systematic publication of seismic recordings.

Similarly, in the College of Engineering and particularly in its Department of Civil Engineering, there developed an early interest in the dynamic characteristics of structural bodies and in attendant structural design problems and, over the years, a growing interest in the response of engineering structures to earthquake forces.

Additionally, there exists at Berkeley a healthy and productive interaction in this field between the geophysicists in the Seismographic Stations and our Department of Geology and Geophysics and those in engineering concerned with this field.

More recently, the College of Engineering, with steady prompting from such individuals as Professors Penzien, Clough, Bouwkamp, and numerous others, undertook theoretical and engineering studies of methodology in earthquake engineering research, and from these efforts came the concept of a laboratory centered on a device for earthquake simulation and study of the effects on prototype structures. There was proposed and officially established in the University an organized research unit now known as the Earthquake Engineering Research Center. After long and ardous efforts, this unit received its first continuing state-funded budget in the present fiscal year.

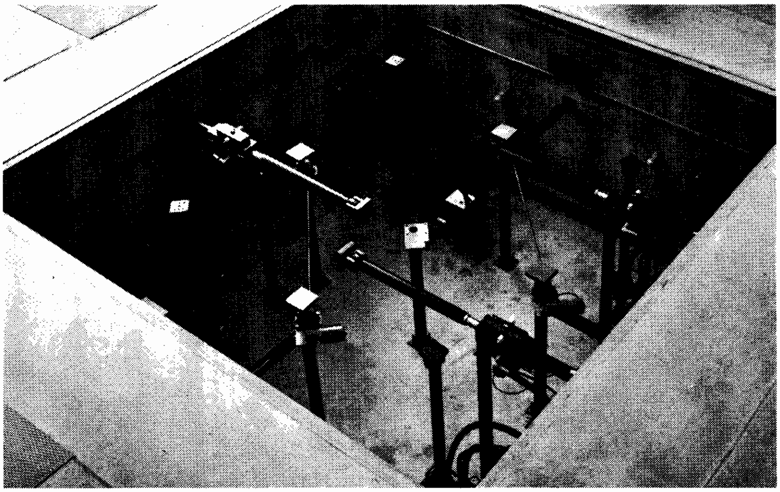
Through the endeavors of a small core of faculty, prominent among which was Professor Penzien, interest was awakened in the National Science Foundation, and from this has come a series of grants that have generously supported research in this field as well as the construction and equipping of this laboratory. The laboratory will be a focus of research in earthquake engineering, and it will be an immeasurably valuable resource in the training of students, particularly at the graduate level.

Still another step, I am pleased to note, has been taken to enhance the effectiveness of the University-National Science Foundation program in earthquake engineering. The sponsors of our Center have wisely recognized that excellent scientific work often languishes for years in the scientific journals and libraries, unnoticed by those in practice. Further, it can safely be said that, beyond the great gap in our fundamental knowledge of seismic phenomena and their effects on engineering structures, we often do not today apply in current designs all the knowledge already in hand. With these circumstances in mind, the National Science Foundation, in collaboration with the University of California at Berkeley and the California Institute of Technology, has established a National Earthquake Engineering Information Service whose mission will be to support communication among all parties—both scientific and applied—who work in this field.

It is of more than passing interest that the role of the National Science Foundation in these developments be fully recognized. The University is grateful for the Foundation's support in this vital research-educational enterprise and takes particular note of the sustained concern and guidance of Dr. Michael P. Gaus, Program Director in the Foundation's Division of Engineering and—more recently—of Dr. Charles C. Thiel, Program Manager, Advanced Technological Applications, in the Foundation's RANN program.

In brief, we have in being the essential elements of a highly successful undertaking. There is a problem of great scientific interest and urgent public concern. Strong and broad Univeristy participation in this field is fully consistent with the University's traditional commitment to teaching, research, and public service. There is in the University an extensive history of distinguished research in the scientific and engineering aspects of seismic disturbances and a continuing body of dedicated staff and students. There is now operational a highly advanced facility in support of new research in earthquake engineering and, coupled with it, an organization designed to assist in prompt professional examination and application of findings. There exists a cordial and firm collaboration within and among major Universities and a crucial supporting agency of our federal government—and an engineering profession that will support this laboratory and benefit from its work.

For the above reasons, and with great optimism, I am honored formally to welcome this laboratory and its undertakings into the family of institutions that comprise the University of California and its Berkeley campus.



Hydraulic Driving System in Pit Below Table

SHAKING TABLE CHARACTERISTICS

MATERIAL: REINFORCED CONCRETE WITH PRE-STRESSING

PLAN DIMENSIONS: 20 BY 20 FT.

WEIGHT: 95,000 LB.

MAXIMUM TEST STRUCTURE WEIGHT: 115,000 LB.

MAXIMUM TEST STRUCTURE HEIGHT: 40 FT.

COMPONENTS OF MOTION: 1 VERTICAL–HORIZONTAL

TYPES OF MOTION:
PERIODIC
RANDOM

DISPLACEMENT RANGE:
HORIZONTAL – 12 IN.
VERTICAL – 4 IN.

MAXIMUM ACCELERATION (TABLE FULLY LOADED):
HORIZONTAL – 0.75 g
VERTICAL – 0.5 g

POWER OF HYDRAULIC DRIVING SYSTEM:
AVERAGE – 600 HP.
PEAK – 1200 HP.